

ANGULAR DISTRIBUTIONS
OF EVAPORATION RESIDUES
FROM NEAR-BARRIER FUSION
OF $^{32,36}\text{S}$ ON A ~ 100 NUCLEI

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OF $^{32,36}\text{S}$ ON A ~ 100 NUCLEI

DISSERTATION

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ZUSAMMENFASSUNG

Die Winkelverteilungen von Verdampfungsrestkernen aus der Fusion von $^{32,36}\text{S}$ Ionen mit $^{92,94,96,98,100}\text{Mo}$, $^{100,101,102,104}\text{Ru}$, ^{103}Rh und $^{104,105,106,108,110}\text{Pd}$ in der Nähe der Barriere wurden im Bereich von 3 bis 11 Grad im Laborsystem gemessen. Ein aus konzentrischen Ringen bestehender Parallelplattenzähler in azimuthaler 2 Geometrie wurde entwickelt, mit dem es möglich ist, bei sehr hohen Zählraten mit Hilfe einer Flugzeitmessung mit gepulstem Strahl Fusionsprodukte von elastisch gestreuten Projektilen zu unterscheiden.

Die relativen Ausbeuten für die vier häufigsten Ausgangskanäle wurde für alle Projektil-Target-Kombinationen bei zwei Einschußenergien bestimmt, indem die Winkelverteilungen, die man nach dem Monte-Carlo Programm TRANMI erwartet, an die gemessenen Winkelverteilungen der Verdampfungsrestkerne angepaßt wurden. Die so erhaltenen Verzweungsverhältnisse wurden mit den Vorhersagen der Hauser-Feshbach-Theorie unter Verwendung des Computerprogramms CASCADE verglichen.

Die totale Nachweiswahrscheinlichkeit für das Münchner HF-Rückstoßspektrometer wurde aus den Verzweungsverhältnissen bestimmt, wobei der Einfluß von Vielfachstreuung berücksichtigt wurde, und mit derjenigen verglichen, die man vorher aus der Geschwindigkeits-Verteilung der Verdampfungsrestkerne erhalten hatte. Die neuen Nachweiswahrscheinlichkeiten wurden aus einer genaueren Messung des Alpha-Verdampfungs-kanals bestimmt als diejenigen, die ursprünglich an die Geschwindigkeiten angepaßt wurden, die Ergebnisse beider Messungen stimmen innerhalb der Fehler überein.

Die Anisotropie, die für den Alpha-Kanal benötigt

wird, um die gemessenen Winkelverteilungen der entsprechenden Restkerne wiederzugeben, ist größer als die, welche bei einer Verteilung des Drehimpulses erwartet wird, wie sie aus einem statistischen Modell folgt. Diese Erhöhung der Anisotropie legt eine Erklärung im Rahmen von Fluktuationen der Barriere nahe, die zu einem höheren mittleren Drehimpuls für die Bildung des Compoundkerns führt und -gleichzeitig- die Erhöhung des Wirkungsquerschnitts für Subcoulombfusion beschreibt.

ABSTRACT

The angular distributions of evaporation residues from near-barrier fusion of $^{32,36}\text{S}$ ions with $^{92,94,96,98,100}\text{Mo}$, $^{100,101,102,104}\text{Ru}$, ^{103}Rh , and $^{104,105,106,108,110}\text{Pd}$ were measured in the range of 3 to 11 degrees in the laboratory system. A multi-ring parallel-plate avalanche counter (MPAC) was developed in a 2π -azimuthal geometry which allowed to discriminate fusion events from elastic scattered projectiles at very high counting rates by time-of-flight against the pulsed projectile beam.

The relative yield of the four most abundant exit evaporation channels has been extracted for all target - projectile combination at two bombarding energies, by fitting the angular distributions expected for each channel as obtained from the Monte-Carlo program TRANMI to the measured angular distribution of the evaporation residues. The resulting relative yields were compared with the predictions of the Hauser-Feshbach Theory employing the computer code CASCADE.

The total detection efficiency for the Munich RF-Recoil Spectrometer was obtained from the relative yields, taking into account the effect due to multiple scattering, and compared with that obtained previously from the recoil velocity distributions. The new efficiencies are derived from a more accurate measurement of the alpha-evaporation channel than those originally determined by the velocity fits, the results of both measurements agree within the experimental uncertainties.

The anisotropy required for the alpha-evaporation channel that reproduces the measured angular distribution of the corresponding residues is greater than that predicted by an angular momentum distribution derived from a statistical

model. This anisotropy enhancement suggests an explanation in terms of barrier fluctuation effects which predicts a larger mean angular momentum for compound nucleus formation and - at the same time - describes the enhancement of sub-barrier fusion.

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REFERENCES

1. INTRODUCTION

During the last few years there has been a significant increase in the available experimental information on complete fusion cross sections at energies around the Coulomb barrier.

These measurements were originally stimulated by the need of astrophysicists that require precise sub-barrier fusion cross sections to put forth explanations of nuclear synthesis models for calculating thermonuclear fusion rates in stellar interior, for light systems such as $^{12}\text{C} + ^{13}\text{C}$, $^4\text{He} + ^{12}\text{C}$ etc.

Another stimulation were the attempts to create superheavy elements with little excitation energy for the compound nucleus, in order to increase their surviving chance against fission. Sub-barrier fusion is a doorway to cool compound formation.

For all energies well below the s-wave interaction barrier the cross sections for complete fusion between two sufficiently heavy ions decrease much less steeply with decreasing energy than predicted by models that employ an one-dimensional potential energy function for the quantum tunneling¹⁻⁴ as is shown in fig.1.

Simple barrier penetration models as parameterized for example by the Wong formula⁵, have proven successful only in fitting the fusion cross sections for light systems.

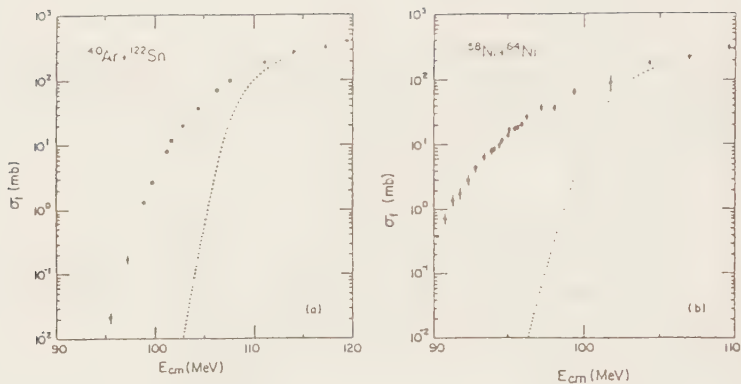


Fig.1: Fusion cross sections for $^{40}\text{Ar} + ^{122}\text{Sn}$ and $^{58}\text{Ni} + ^{64}\text{Ni}$ compared with penetrability calculations (dotted line) employing standard ion-ion potentials and frozen shapes (cf.ref.3 and 6).

Another remarkable observation is that there are fusion excitation functions that do not scale with the number of nucleons. Removing the geometrical differences in the Ni + Ni data of Beckerman et al.⁶, before comparing them, it is surprising that $^{58}\text{Ni} + ^{64}\text{Ni}$ does not behave as a mediate system between the symmetric systems, as it is suggested in fig.2.

This fact suggests the necessity to consider nucleonic exchanges preceding the fusion reaction⁶.



Fig.2: Reduced excitation functions associated with the reactions $^{58,64}\text{Ni} + ^{58,64}\text{Ni}$. Filled triangles: $^{64}\text{Ni} + ^{64}\text{Ni}$, open circles: $^{58}\text{Ni} + ^{64}\text{Ni}$ and open triangles: $^{58}\text{Ni} + ^{58}\text{Ni}$. The data were taken from ref.6.

Under the assumption that the sub-coulomb barrier fusion can be accounted for by an one-dimensional potential energy function, Balentekin et al.⁷ obtained an inversion formula for the "classical turning points" as a function of the experimental cross section. This "thickness function" when used to reconstruct the Coulomb barrier gave rise to unphysical barrier shapes especially when the mass number of the target and of the projectile were greater than 40, as is shown in fig.3.

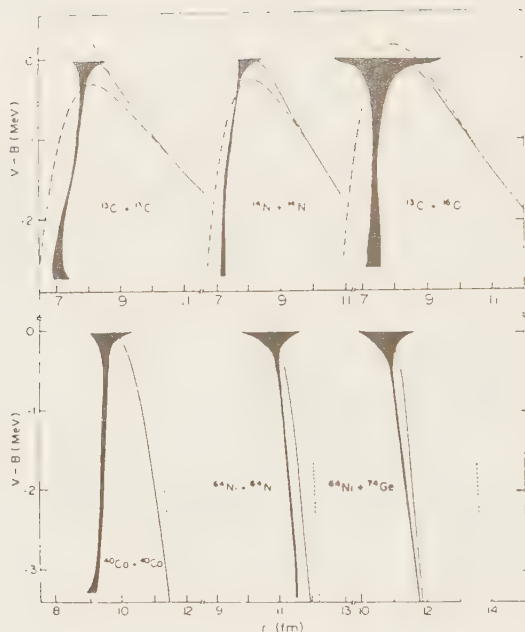


Fig.3: Effective one-dimensional potential barrier⁷ for $^{13}\text{C} + ^{13}\text{C}$, $^{14}\text{N} + ^{14}\text{N}$, $^{13}\text{C} + ^{16}\text{O}$, $^{40}\text{Ca} + ^{40}\text{Ca}$, $^{64}\text{Ni} + ^{64}\text{Ni}$ and $^{64}\text{Ni} + ^{74}\text{Ge}$ extracted from fusion data. The short dashed line is due to the point Coulomb potential, the long dashed curve in the upper figure denotes the unmodified KNS potential. The full line describes the KNS potential readjusted in order to fit the peak positions and the shaded region indicates the errors associated with the 'thickness function' (cf.ref.7).

These unnatural looking potentials suggest that such one-dimensional calculations are inadequate for an understanding of these fusion mechanism.

Several attempts have been made to account for this sub-coulomb fusion enhancement, but until now none seems to be completely successful in explaining what degrees of freedom control this process.

There is evidence that particle transfer⁸⁻¹¹ and inelastic excitations¹²⁻¹⁷ are the basic mechanisms by which energy and angular momentum can be transferred from the relative motion to the internal degrees of freedom and which therefore play a role in determining the sub-barrier fusion.

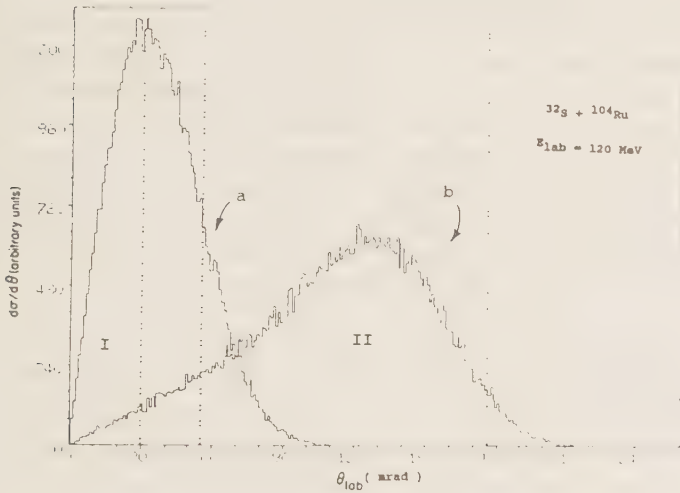


Fig.4: Typical angular distributions of neutron-(curve a) and of alpha-evaporation residues (curve b) simulated by the Monte Carlo evaporation code TRANMI¹⁸ for the near-barrier fusion of even projectiles $^{32,36}\text{S}$ on A-100 nuclei. The evaporation process was assumed to be isotropic in the center-of-mass system (CM-system). The regions I and II are related to the acceptances of the Munich recoil spectrometer and the ring detector (developed in this work), respectively.

Stimulated by these investigations the Munich RF-Recoil Spectrometer¹⁹ has been used to obtain a number of

experimental sub-coulomb fusion data for intermediate-mass heavy ions²⁰. The recoil spectrometer allows the separation and identification of recoils within a maximum solid angle of 3msr. It therefore loses considerable detection efficiency for alpha-evaporation residues whose kinematic angular spread is much larger than this acceptance angle (see fig.4).

The fig.4 demonstrates that an independent knowledge of the contribution of the alpha-residues (which in the experiments just mentioned amounted to 10-25%) is very important in order to avoid large experimental errors in the total fusion cross sections deduced from residue intensities detected by the recoil spectrometer. In the original experiments the fractions of the alpha-evaporation residues were obtained from their small fractional intensity detected in region I with the recoil spectrometer, using a method which will be described in a later chapter.

In order to get a more accurate determination of the alpha-evaporation residues a multi-ring parallel-plate proportional counter (MPAC) was developed to measure the angular distribution in a range that covers substantially the kinematic spread of this evaporation channel.

The measurement of these angular distributions of the compound residues from fusion of $^{32,36}\text{S}$ with Mo-, Ru-, Rh- and Pd-isotopes have been carried out at 120 MeV and 114 MeV in the laboratory system (L-system).

The principle of operation and description of the MPAC as well as the experimental and electronic set-up are described in chapter 4.

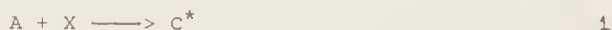
In chapter 5 it is shown how the data are evaluated in order to obtain the relative intensities of the most predominant evaporation residues and from them the total detection efficiency of the Munich recoil spectrometer for all target-projectile combination.

In chapter 6 the main results are presented concerning the angular distributions as well as the deduced relative residue intensities and the efficiency of the Munich heavy-ion spectrometer.

The fractions of the alpha-evaporation channels are compared with those originally derived from the recoil velocity distributions and those predicted with the computer code CASCADE. The observed anisotropy enhancement for the alpha-channel agrees with a broader spin distribution than one-dimensional barrier penetration models would predict and can be interpreted as an indication of barrier fluctuations in accordance but independently of the enhancement of the sub-barrier fusion cross sections. These results are presented in chapter 7.

2. ANGULAR DISTRIBUTION OF EVAPORATION RESIDUES

If the energy of the incident nucleus A is large enough to surmount the mutual Coulomb barrier of target and projectile (but is not too far above the barrier), the formation of a compound nucleus will be the most important reaction channel at this energy:



The compound nucleus C is, in general, excited to an energy region where many levels overlap. If (as usual) the experimental beam energy resolution is not much smaller than the average total width of these levels, interference effects cancel and the formation and the de-excitation of the compound nucleus become independent. In this case the cross section (at energy E, angular momentum L and parity π) of decay into a particular channel α may be written as a product

$$\sigma(\alpha) = \sigma_c(E, L, \pi) P(\alpha, E, L, \pi) \quad 2$$

where σ_c is the cross section for forming the compound nucleus and P is the probability of decays into channel α . Under the same conditions $\sigma(\alpha)$ varies smoothly with energy and angle.

The excitation energy of the compound nucleus amounts to at least the effective threshold energy (E_{α}^{eff}) of the fragmentation $\alpha = (A, X)$, which is obtained by the sum between the Coulomb barrier $V_B(\alpha)$ and the binding energy $Q(\alpha)$ of the two nuclei,

$$E^* \geq E_{\alpha}^{\text{eff}} = V_B(\alpha) + Q(\alpha) \quad 3$$

Another feature of a compound nucleus produced in a

heavy ion collision is that it is excited preferably with high spin. According to the semi-classical relation for the centrifugal energy :

$$E_c = \frac{L(L+1)}{2\mu r^2} \hbar^2 \quad 4$$

one finds that the maximum compound spin is to first order equal to L , the angular momentum in "grazing" collision of the colliding ions with "touching" surfaces (interaction radius). In eq.4 μ denotes the reduced mass and r the center-to-center distance.

In medium heavy systems like the ones discussed in this work the compound angular momentum is not large enough to allow fission. In this case neutron evaporation will be the most favoured compound nucleus decay channel, followed by the evaporation of other particles like protons and alpha-particles, giving rise to a chain of sequential decays. In addition to these sequential decays prompt or delayed gamma rays and X-rays are also emitted.

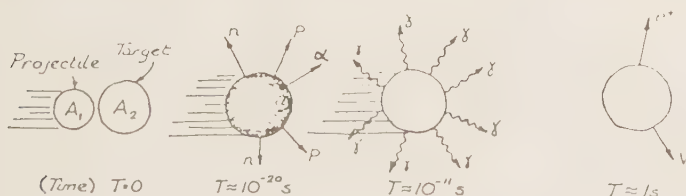


Fig.5: Time sequence of events in a fusion evaporation reaction.

Considering that the evaporation process of a compound nucleus is purely statistical and taking into account only the conservation of energy and total linear momentum of this system, this process leads to an isotropic angular distribution (in CM-system) of the recoiling evaporation residues. The corresponding angular distribution can be written in the form

$$W(\theta) = \text{const.}$$

5

similarly the differential cross section per unit solid angle has the form

$$\frac{d\sigma(\theta)}{d\Omega} = \text{const.}$$

6

A more realistic description of an evaporation process has also to consider restrictions on the directions of the outgoing fragments due to the angular momentum distribution of the compound nucleus. The angular momentum of a compound nucleus formed by absorption of an incident particle prefers to be directed perpendicularly to the incident beam, depending on the size of the entrance channel spin which is generally small.

With respect to the angular momentum the level density distribution of the residual nucleus is of the following form:

$$\rho(J) = \rho_0 (2J+1) \exp\left[-\frac{J(J+1)}{2\sigma^2}\right] \quad 7$$

where J is the angular momentum of the residual nucleus and σ^2 is the level density angular momentum cut-off parameter, being expressed as a function of the nuclear moment of inertia $\mathcal{J}$ and the nuclear temperature T by the following relation:

$$\sigma^2 = \frac{\mathcal{J} T}{\hbar^2} \quad [T] = [\text{energy}] \quad 8$$

Due to the statistical nature of the decay, the evaporation of a particle by the excited compound nucleus will prefer states of lower angular momenta. At a given orbital angular momentum of the particle (which is limited by the centrifugal barrier) this is accomplished best if the highest possible level density in the residual nucleus is reached for small angular momenta. Consequently the outgoing particle has its orbital angular momentum preferentially

anti-parallel to the angular momentum of the compound nucleus. Classically one may consider the particles centrifuging off at the equator plane of the rotating compound nucleus, an effect already leading to an anisotropy in the CM-system.

Considering the above (statistical) coupling between the angular momentum L of the compound nucleus and the orbital angular momentum l of the evaporated particle, a formalism was proposed by Ericson and Strutinsky²¹ resulting in an expansion in terms of the even Legendre polynomials for the angular distribution of evaporated particle of energy E_2 and angular momentum l in the following form :

$$W(\theta, E_2) = \frac{1}{4\pi} \sum_{k=0}^{\infty} \frac{(-)^k (4k+1) \left[\frac{(2k)!}{(2^k k!)^2} \right]^2 j_{2k}(2i\alpha_f L l) P_{2k}(\cos\theta)}{j_0(2i\alpha_f L l)} \quad 9$$

where θ is the angle between the direction of the outgoing particle and the incident beam in the CM-system. The quantities $j_{2k}^{(x)}$ are spherical Bessel functions and α_f is related to the moment of inertia $\mathcal{J}$ and the nuclear temperature T of the residual nucleus by the relation

$$\alpha_f = \frac{\hbar^2}{2\mathcal{J}T} = \frac{1}{2\sigma^2} \quad 10$$

Eq.9 describes the angular distribution of an evaporated particle of given orbital angular momentum l from a compound nucleus of angular momentum $J = L$. Projectile, target and evaporated particle are considered spinless.

To obtain the final angular distribution $W(\theta, E_2)$ a proper averaging over $J = L$ and l has to be performed

$$W(\theta, E_2) = \text{const.} \int L T_1(L) dL \int l T_2(l) S(l, l) W d l \quad 11$$

where $S(L, l)$ is a weighting factor describing level

densities²¹. The quantities T_1 and T_2 are the transmission coefficient for the compound nucleus formation and for a subsequent particle evaporation, respectively.

One result of the theory is that, if the level density is proportional to $2J + 1$ (large value of $\bar{G}$, see eq.7) the angular distribution will be isotropic. Generally, however, there will be an angular correlation between the orbital angular momentum ℓ of an evaporated particle and the angular momentum L of the compound nucleus. Two extreme cases are considered; a strong-coupling and a weak-coupling.

In the strong-coupling (or classical limit) channel spins and the quantum properties of angular momentum are neglected. The consequence is an angular distribution in the CM-system in the following form:

$$W(\theta) \propto \frac{1}{\sin \theta} \quad 11$$

The eq.11 demonstrates that this angular distribution is extremely forward-backward peaked, as is shown in fig.6. Classically it can be understood if the evaporation takes place in the equator plane of the angular momentum L , with $d\bar{G}/d\theta = \text{const.}$

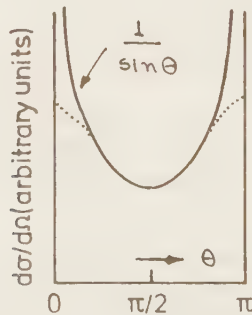


Fig.6: Schematic representation of the angular distribution in the form $\frac{d\bar{G}(\theta)}{d\Omega}$ in the CM-system in the strong-coupling limit.

In a quantal system the just mentioned extreme alignment is not possible and the lower the orbital angular momentum of the evaporated particle the less perfect the alignment can be. As a result experimentally observed angular distributions of products from heavy ions are anisotropic, but fall considerably short of following a $1/\sin\theta$ law, particularly at 0° and 180° (dotted extension in fig.6).

In the weak-coupling approximation the spherical Bessel functions can be approximated by the first term of a power expansion

$$j_{2k} = \frac{(2i\alpha_f l L)^{2k}}{(4k+1)!!} \quad 9.b$$

and the expansion in eq.9 limited to $k \leq 1$ resulting in

$$W_{L,l}(\theta, E_2) \sim 1 + \frac{\alpha_f^2 L^2 l^2}{2} \cos^2 \theta \quad 12$$

In addition the weak-coupling approximation leads to $S(L, l) \approx 1$. Consequently the averages according to eq.9a finally gives

$$W(\theta) \propto 1 + A_2 \cos^2 \theta \quad 13$$

where

$$A_2 = \frac{\langle L^2 \rangle \langle l^2 \rangle}{8 G^4} \quad 14$$

Since $A_2 > 0$ according to eq.13' the angular distribution, like in the strong-coupling limit, exhibits maxima at the forward and backward directions and the term $\cos^2 \theta$ guarantees the symmetry with respect to 90° .

It is worth noting that also in the case of a decay between definite (isolated) states in the compound and in the residual nucleus one finds a forward-backward peaking which increases with increasing initial spin and increasing orbital angular momentum l_α of the particle. Under certain conditions and if again stretched transition is assumed ($J_f = J_i - l_\alpha$) one has in this case

$$W(\theta) = 4\pi \sum_{m_\alpha} \left(l_\alpha m_\alpha J_f M_f \middle| J_i \frac{1}{2} \right)^2 \left| Y_{l_\alpha}^{m_\alpha}(\theta) \right|^2 \quad 15$$

as illustrated for two transitions in fig.7.

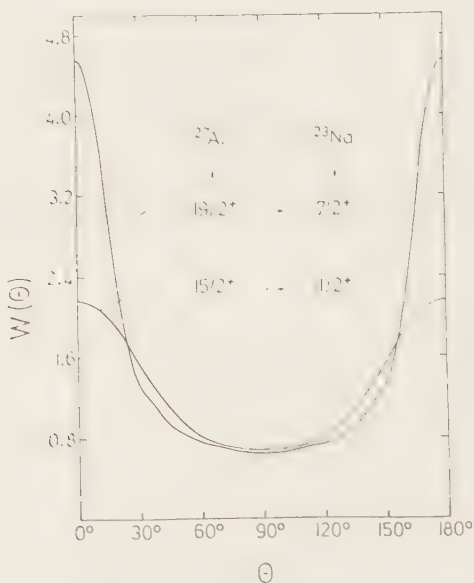


Fig.7: Angular correlation functions for two different alpha-transitions between states with definite spins (cf. I. Weidl et al.²³).

In the weak-coupling case it must be noted that the dependence of the angular distribution on the energy of the evaporated particle is contained in the factor $\langle \chi^2 \rangle$ since the magnitude of this quantity depends on the energy of the evaporated particle. A more detailed description of the parameter A_2 is found in sec.7.4.

The strong-coupling and the weak-coupling may be characterized by the following conditions

$$\frac{\langle L^2 \rangle \langle \ell^2 \rangle}{G^2} \gg 1, \text{ strong-coupling} \quad 16$$

$$\frac{\langle L^2 \rangle \langle \ell^2 \rangle}{G^2} \lesssim 1, \text{ weak-coupling} \quad 17$$

In this work typical ratios presented by eqs.16-17 are about 0.40, suggesting a weak-coupling description for the angular distribution. Ratios up to 1.5 were determined by U.Arlt et al.²⁴ and the weak-coupling case was successfully employed to describe their experimental angular distributions.

In the laboratory system (L-system) the evaporation of particles from the excited compound nucleus leads to distributions in angles of recoils, which reflect the kinematics of the fusion process. The main purpose in discussing this kinematics is to illustrate shapes of angular distributions in the L-system dependent on an assumed form for the angular emission probability in the CM-system as well as the average angular range.

Consider a beam projectile of mass M_p and kinetic energy E_p colliding with a target of mass M_t to form a compound nucleus with a recoil velocity $\vec{V}_c$ along the beam direction. The evaporation of a particle from the compound system imparts to the residual nucleus a resultant velocity $\vec{V}$ in the CM-system, directed at a center-of-mass angle Θ

related to the beam direction, as is represented by the velocity diagram shown in fig.8.

According to fig.8 the residual nucleus will be observed at an angle θ_L expressed by

$$\tan \theta_L = \frac{v \sin \theta}{v_c + v \cos \theta} \quad 18$$

where $v_c^2 = 2 M_b M_b / (M_b + M_t)^2$ 19

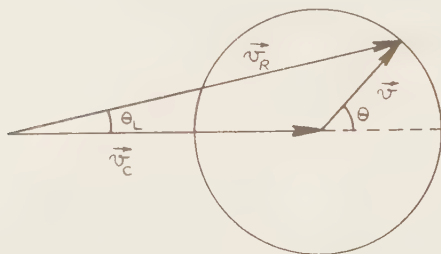


Fig.8: Velocity diagram used to represent the kinematic properties of evaporation residues. The quantities $\vec{v}_c$ and $\vec{v}_R$ are the laboratory velocities of the compound nucleus and residue, respectively.

Considering all the recoil nuclei, an average square tangent for the zenithal angle can be given by

$$\langle \tan^2 \theta_L \rangle = \frac{\int_0^\pi \left[\frac{v \sin \theta}{v_c + v \cos \theta} \right]^2 W(\theta) \sin \theta \, d\theta}{\int_0^\pi W(\theta) \sin \theta \, d\theta} \quad 20$$

where $W(\theta)$ is the angular distribution of the recoils in the CM-system.

Rearranging the squared factor in the numerator of eq.20 and using the binomial series to expand $[1 + v/v_c \cos \theta]^{-2}$,

this equation can be solved if v/v_c is less than unity. Generally one has $v \ll v_c$ and therefore $\tan^2 \theta_L \approx \theta_L^2$. In this case one gets for isotropic evaporation and weak-coupling the average squared $\langle \theta_L^2 \rangle$ to order $(v/v_c)^3$

$$\langle \theta_L^2 \rangle = 2 \langle v^2 \rangle / 3 v_c^2 \quad 21$$

$$\langle \theta_L^2 \rangle = 2 \langle v^2 \rangle / 3 v_c^2 \left[\frac{1 + A_2/5}{1 + A_2/3} \right] \quad 22$$

respectively²⁵.

For values of A_2 relevant in this work ($A_2 \approx 0.40$) the effect of the anisotropy in the CM-system on $\langle \theta_L^2 \rangle$ is negligible. Information on A_2 can be obtained, however from the detailed shape of the angular distributions, as will be shown later.

The quantity $\langle v^2 \rangle$ is evaluated by the average total kinetic energy $\langle E_k \rangle$ of the evaporated particles in the CM-system. The distribution of v (or E_k) can be assumed to be a Maxwellian function, that is

$$H(E_k) dE_k = \text{const.} \sqrt{E_k} e^{-E_k/T} dE_k \quad 23$$

For neutron evaporation the average velocity can be expressed as

$$\langle v^2 \rangle = \frac{3T}{m} \quad 24$$

where m is the mass of the evaporated neutron. Therefore the average energy of the evaporated neutron is given by

$$\langle E_n \rangle = \frac{3}{2} T \quad 25$$

For charged evaporated particles the energy distributions are shifted upwards due to the Coulomb barrier. Therefore the average energy for proton and alpha-particle can roughly be estimated by

$$\langle E_p \rangle = V_{B,p} \quad 26$$

$$\langle E_\alpha \rangle = V_{B,\alpha} \quad 27$$

where the quantities $V_{B,p}$ and $V_{B,\alpha}$ are the Coulomb barrier for the proton and alpha-particle evaporation, respectively.

Assuming as in this work typical nuclear temperature (1.6 MeV) and Coulomb barriers for proton and alpha-particle evaporation of 9 MeV and 18 MeV, respectively, the following ranges are obtained:

$$\sqrt{\langle \theta_L^2 \rangle_n} \approx 15 \text{ mrad} \quad 28$$

$$\sqrt{\langle \theta_L^2 \rangle_p} \approx 60 \text{ mrad} \quad 29$$

$$\sqrt{\langle \theta_L^2 \rangle_\alpha} \approx 110 \text{ mrad} \quad 30$$

These numbers give a clear indication that the measurement of the angular distribution of the evaporation residues within the strong forward peaked Rutherford scattered projectile beam is very difficult. As will be shown later, the elastic scattered events are expected to be up to 8 orders of magnitude larger than the corresponding fusion events.

The estimated angular ranges are associated with one particle evaporation. A more realistic calculation has to consider multi-particle evaporation, which is a typical feature for a compound nucleus decay.

Ideally, one would like to have an analytical expression for the distribution of the recoil velocity that incorporate the effects arising from this sequential evaporation.

Assuming that the angular distribution for all evaporated neutrons is isotropic and their velocity

distribution is Maxwellian, Hilscher et al.²⁶ expressed the angular distribution in the L-system of the corresponding recoils as

$$\frac{dG(\theta_L)}{d\Omega_L} \approx N \cos^2 \theta_L \exp(-\sin^2 \theta_L / 2 G^2) \quad 31$$

where

$$G^2 = x \frac{m T_{MeV}}{M_{ER}^2 v_c^2} \quad 32$$

with x being the average number of evaporated neutrons of mass m , leading to a residual nucleus of mass $M_{ER} = (M_b + M_t) - xm$.

Calculating $\langle \theta_L^2 \rangle$ from eq.31 under the assumption of $\theta_L \ll 1$ (that is $G \ll 1$) one gets $G^2 = 2 \langle \theta_L^2 \rangle$. Hereby eqs.32-21 become consistent.

An analytical expression for emission of charged particles is not trivial since their energy distributions are shifted upwards by the corresponding Coulomb barriers. In accordance with eqs.29-30 this leads to a broader angular distribution.

In order to determine the dimensions of the ring detector and to analyse the measured angular distributions in terms of the various evaporated channels numerical calculations were carried out for multi-particle evaporation using the Monte Carlo program TRANMI, as shown in fig.9. The dimensions of the detector were chosen as to allow the measurement of the angular distributions in L-system in the range of 50 to 180 mrad.

The fig.9d shows also the effect of a typical anisotropic angular distribution, of the weak-coupling type with $A_2=0.40$.

$$^{32}\text{S} + ^{104}\text{Ru}, E_{\text{lab}} = 120 \text{ MeV}$$

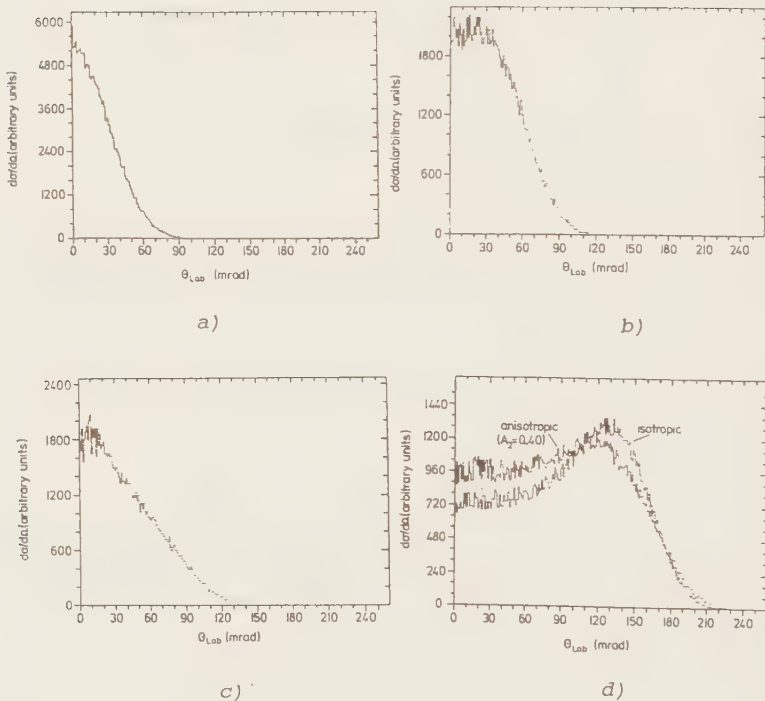


Fig.9: A typical angular distribution for the evaporation residues resulting from a) (n,n...), b) (p,n...) c) (p,p,n...) and d) (α,n...)-evaporation events*). The evaporation processes are assumed to be isotropic in CM-system (except d) and the average kinetic energy of the evaporated particles is 1.6, 9 and 18 MeV for neutrons, protons and alpha-particles, respectively.

*) n... denotes a varying number of neutrons depending on the statistics of energy consumption during the evaporation.

3. SUB-BARRIER FUSION OF HEAVY IONS

3.1 REMARKS ON BARRIER PENETRATION MODELS

Generally to account for the fusion of two heavy ions a semiclassical friction-free model is employed. The condition for fusion is that there exists a 'pocket' in the effective ion-ion potential, $V(r, L)$, which can be expressed as the sum $V(r)$ between the nuclear and Coulomb potential to the centrifugal potential

$$V(r, L) = V(r) + \frac{\hbar^2}{2\mu r^2} \frac{L(L+1)}{2} \quad 33$$

as it is shown in fig.10.

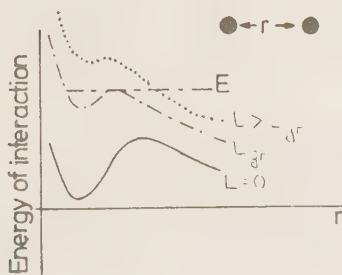


Fig.10: Schematic representation for the interaction potential between two nuclei a distance 'r' apart.

Taking into account that the fusion process is cumulative in angular momentum, the fusion cross section can be obtained from the partial wave summation

$$\sigma_f = \pi \lambda^2 \sum_{0}^{\infty} (2L+1) T_L P_L \quad 34$$

where λ is the asymptotic wavelength and P_L is the probability that a partial wave L fuses once it has penetrated the effective barrier. The probability of penetrating the barrier is given by the transmission coefficient T_L .

The contribution of each partial wave L to σ_f is determined only by the transmission coefficient T_L , if it is assumed that P_L is unity. This model allows to discuss the fusion cross section in terms of the transmission coefficients T_L .

The sharp cut-off model considers the colliding nuclei to be infinitely strongly absorbing spheres. According to this assumption the fusion reaction takes place if the spheres overlap and does not take place if the spheres do not touch.

The classical trajectories which lead to such a contact are defined by a certain set of impact parameters which will be allowed for a given energy. Each of these impact parameters can be associated with an angular momentum state of the system.

If the interaction potential is only radially dependent then there exists a maximum L_{gr} above which $T_L = 0$ and below which $T_L = 1$. From this entirely classical point of view the transmission coefficient abruptly changes from 1 to 0 when the barrier of the effective potential becomes greater than the projectile energy. Consequently, the fusion reaction will not be expected for energies below the coulomb barrier V_B (s-wave barrier height) as is shown in fig.11.

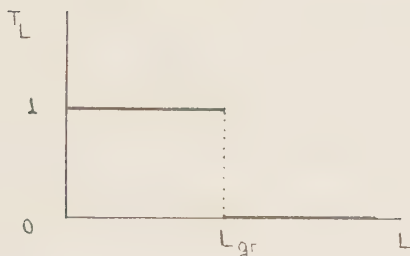


Fig.11: Schematic diagram for the transmission coefficient according to the sharp cut-off approximation.

Under these assumptions, eq.34 reduces to

$$\sigma_f = \pi \lambda^2 (L_{gr} + 1)^2 \quad 35$$

Equating at the point of contact the coulomb barrier V_B and the centrifugal potential with the center-of-mass energy E (see eq.4), an expression for L_{gr} can be obtained

$$L_{gr} = 0.22 R \sqrt{\frac{A_1 A_2}{A_1 + A_2} (E - V_B)} \quad 36$$

where R is the interaction radius (the sum of the two colliding nuclear radii in fm) and A_1 and A_2 are the mass numbers of projectile and target, respectively (E and V_B in MeV).

The expression for L_{gr} can be substituted into eq.35 leading to the simple form:

$$\sigma_f = \pi R^2 \left(1 - \frac{V_B}{E}\right) \quad 37$$

This classical approximation was often employed for rough barrier and radius estimations. It is, of course,

valid only for $E > V_B$.

Allowing for quantum mechanical corrections due to tunnelling through the barrier, the sharp step function displayed in fig.11 smooths out, and acquires the shape depicted in fig.12.

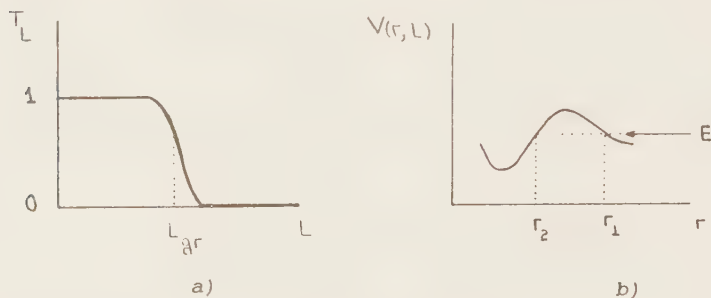


Fig.12: Schematic representation for a realistic transmission coefficient a) and for quantum tunneling through the potential depicted on the right b).

In order to get a quantitative description for the penetrability of this one-dimensional barrier, the transmission coefficient is calculated for $E < B_L$ (effective barrier height for angular momentum L) in the Jeffreys-Wentzel-Kramers-Brillouin (JWKB) approximation²⁷ to be

$$T_L(E) = \left[1 + \exp(S_L) \right]^{-1} \quad 38$$

where S_L is the classical action integral, evaluated between the outer and inner turning points r_1 and r_2 , respectively

$$S_L = 2 \int_{r_1}^{r_2} \left[\frac{2\mu}{\hbar^2} (V(r, L) - E) \right]^{1/2} dr \quad 39$$

Often the potential near the barrier top is

approximated in this region by an inverted harmonic oscillator, for which the transmission coefficient is given exactly (also for $E > B_L$) by the Hill-Wheeler formula²⁸

$$T_L = \left[1 + \exp \left\{ \left(\frac{2\pi}{\hbar \omega_L} \right) (B_L - E) \right\} \right]^{-1} \quad 40$$

where again B_L is the effective barrier height for the partial wave with angular momentum L . The quantity $\varepsilon = \hbar \omega_L / 2\pi$ is a measure of the barrier thickness and the 'Hill-Wheeler frequency' ω_L is given by

$$\hbar \omega_L = \left| \frac{\hbar^2}{\mu} \frac{d^2 V(r, L)}{dr^2} \right|_{R_L}^{1/2} \quad 41$$

where R_L corresponds to the maximum in the potential $V(r, L)$ and μ is the reduced mass of the system.

The advantage of this 'barrier penetration model' lies in the fact that it contains no free parameters except those determining the effective potential. The Hill-Wheeler formula seems to work quite well for light systems, except in the extreme sub-barrier regions where the effective potential is usually wider than this parabolic approximation. Hence the transmission coefficient is expected to be overestimated in this region. This is the reason why the transmission coefficients must be directly calculated with the JWKB approximation for energies far below the barrier top.

A simple analytic expression for the fusion cross section employing the one-dimensional barrier penetration was carried out by Wong⁵, assuming that the radial position and the thickness of the barrier do not change with angular momentum. Under these assumptions, the eq.40 is substituted into eq.34 and the sum over L replaced by an integral. The following result is obtained

$$\sigma_f = \frac{R_0^2}{2} \frac{\hbar \omega_0}{E} \log \left\{ 1 + \exp \left[2\pi \left(\frac{E - V_B}{\hbar \omega_0} \right) \right] \right\} \quad 42$$

where V_B is the 's-wave' barrier height, R_0 is the average peak position and $\hbar \omega_0$ is the average of all the partial wave barriers. This description provides a very simple fit to fusion data, but it is not detailed enough to direct us towards an explanation of the sub-barrier fusion enhancement. It is, however, often used as a 'standard' to describe the enhancement of measured sub-barrier fusion cross sections relative to what is expected with one-dimensional tunnelling.

The effective potential in eqs.39-41 is given by

$$V(r, L) = V_n(r) + V_c(r) + \hbar^2 \frac{L(L+1)}{2\mu r^2} \quad 43$$

where $V_n(r)$ is the nuclear and $V_c(r)$ is the Coulomb potential.

$V_c(r)$ has the form

$$V_c(r) = Z_1 Z_2 e^2 / r, \quad r \gg R_c \quad 44$$

$$V_c(r) = (Z_1 Z_2 e^2 / 2R_c) (3 - r^2/R_c^2), \quad r < R_c \quad 45$$

where

$$R_c = r_c (A_1^{1/3} + A_2^{1/3}),$$

is the 'touching sphere' radial separation with r_c being a variable parameter.

In section 3.3 the most important features of the proximity potential which was used in this work to describe the nuclear interaction $V_n(r)$ will be described.

3.2 COUPLED CHANNEL APPROACH AND TRUNCATED BARRIER FLUCTUATION FORMALISM

There is evidence arising from experimental results that low energy heavy-ion fusion reaction cross sections are grossly underpredicted by one-dimensional barrier penetration calculations. These experimental fusion data may be accounted for as a consequence of the coupling of intrinsic degrees of freedom of the dinuclear system as it approaches towards a completely fused state.

The simplest generalization of the one-dimensional barrier penetration calculation is to allow the dinuclear system to have one additional channel '2' (representing the excitation of a low-lying collective level in one of the colliding nuclei, or particle transfer), which couples to the entrance channel '1'. The effect of such a coupling has been illustrated by C.Dasso et al.²⁹ in a simple two channel model picture. In this case the two coupled Schrödinger equations for the wave function u in one dimension, can be written as

$$\left[\left(-\frac{\hbar^2}{2\mu} \right) \frac{d^2}{dx^2} + V(x) - E_1 \right] u_1 = -F(x) u_2 \quad 46$$

$$\left[\left(-\frac{\hbar^2}{2\mu} \right) \frac{d^2}{dx^2} + V(x) - E_2 \right] u_2 = -F(x) u_1 \quad 47$$

where μ is the mass corresponding to the x -motion, $V(x)$ is the potential barrier, E_1 and E_2 are the channel energies and $F(x)$ is the coupling interaction.

Neglecting the energy difference between the channels ($E_1 \sim E_2 = E$, i.e. the Q-value of the reaction is vanishingly small) and introducing the wave functions u_+ and u_- by

$$u_1 = (u_+ + u_-)/2, \quad u_2 = (u_+ - u_-)/2 \quad 48$$

it is possible to decouple the Schrödinger equations into a new pair

$$\left[\left(-\frac{\hbar^2}{2\mu} \right) \frac{\partial^2}{\partial x^2} + V(x) \pm F(x) - E \right] u_{\pm} = 0 \quad 49$$

The consequence of this coupling on the tunneling is that the total transmission coefficient

$$T(E) = T_1(E) + T_2(E) = \left[T_+(E) + T_-(E) \right] / 2 \quad 50$$

is given by half the transmission coefficient through a barrier of height $V(x) + F(x)$ plus half the transmission coefficient through a barrier of height $V(x) - F(x)$.

The fig.13-a illustrates the resulting 'split barrier' as a consequence of the presence of a coupling interaction. The fig.13-b demonstrates that when E is smaller than the no-coupling barrier V the transmission is increased by the coupling interaction and when E is larger than V the transmission is decreased, i. e. the coupling enhances the fusion below the barrier and reduces fusion above the barrier.

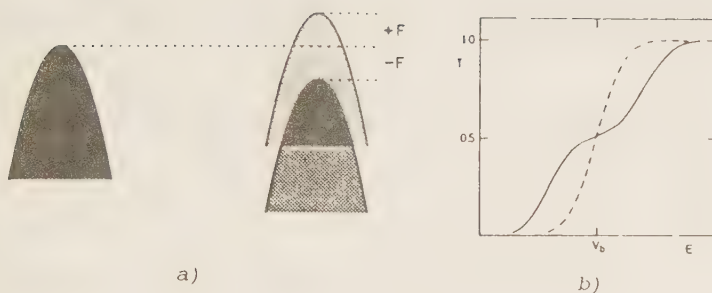


Fig.13: a) Bifurcation of the potential barrier in a two-channel barrier penetration. At the left is the potential barrier confronted by the incoming flux in the absence of coupling. At the right 'everything happens' as if the barrier would split into two, one goes down by the amount of coupling, F , and another that goes up by the same amount. b) Transmission of a two-channel barrier penetration (solid line) compared to the no-coupling limit²⁹.

Considering n channels in the problem formulated as in eqs.46-47, it is possible to decouple the equations for u_i if we treat the formfactor F as being constant (it is assumed for this quantity a representative value of its strength at the barrier position, i.e. $F_{ij} = F_{ij}(r_B)$),

$$\langle i | H_0 + V_{cp} | j \rangle \approx \epsilon_i \delta_{ij} + F_{ij} \equiv M_{ij} \quad 51$$

and

$$\left[\left(-\frac{\hbar^2}{2\mu} \right) \frac{d^2}{dx^2} + V(x) - E \right] u_i = \sum M_{ij} u_j \quad 52$$

where $H_0(\xi)$ is an intrinsic hamiltonian for two colliding nuclei whose internal structures are described by the variables ξ and V_{cpl} is the coupling interaction.

Representing with a vector $\vec{\mu}$ the set of channel wavefunctions μ_i , we can introduce a unitary transformation to a new set of channel wavefunctions $\vec{\gamma}$,

$$\vec{\gamma} = U \vec{\mu} \quad 53$$

where U diagonalizes the coupling matrix M ,

$$\sum_{lk} U_{nl} M_{lk} U_{km}^{-1} = \lambda_m \delta_{nm} \quad 54$$

As a result of this transformation the set of equations for the γ -channels is uncoupled,

$$\left[\left(-\frac{\hbar^2}{2\mu} \right) \frac{d^2}{dx^2} + V(x) + \lambda_m - E \right] \gamma_m = 0 \quad 55$$

The total transmission coefficient can be constructed by adding the contributions of the different channels,

$$T(E) \equiv \sum_m |U_{m0}|^2 T[E, V(r_B) + \lambda_m] \quad 56$$

where the index 0 is used for the entrance channel and $m = 1, 2, \dots$ labels the different eigenchannels. The effect of the coupling is to replace the barrier $V(r_B)$ by a manifold of barriers $(V(r_B) + \lambda_m)$ which confront the incoming flux. The total transmission coefficient is obtained by a weighted average of the transmission coefficients for each barrier of the manifold. The weights $|U_{m0}|^2$ represent the probability for the system to be in the eigenchannel m after the coupling. These weights fulfil the condition $\sum |U_{m0}|^2 = 1$. The quantities $V(r_B) + \lambda_m$ are the effective barriers and the eigenvalues λ_m depend upon the coupling strenghts F_{ij} and Q -values E_i . A second condition

namly $\sum |U_{m0}|^2 \lambda_m = 0$ reflects the fact that some of the effective barriers are decreased while others are increased similarly to the two channel model.

Considering again the the two level problem within the constant coupling approximation but allowing for a finite Q -value, the coupling matrix reads

$$M = \begin{pmatrix} 0 & F \\ F & -Q \end{pmatrix} \quad 57$$

Diagonalizing this two-by-two matrix one obtains

$$\lambda_{\pm} = (-Q \pm \sqrt{4F^2 + Q^2})/2 \quad 58$$

and

$$|U_{m0}|^2 = |U_{\pm}|^2 = \frac{F^2}{F^2 + \lambda_{\pm}^2} \quad 59$$

This result can be visualized in the following figure:

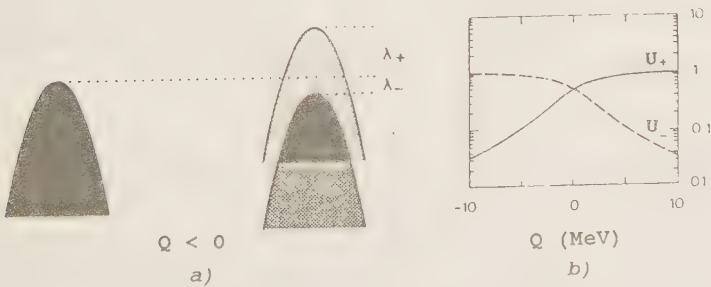


Fig.14: a) Similarly, as in fig.13a, the uncoupled barrier splits into two. However, one goes down by an amount λ_- , and another goes up by a different amount λ_+ . b) overlap probabilities in a two channel problem as a function of Q ($F=1\text{MeV}$)²⁹.

The fig.14 demonstrates that even for negative Q -value channels there is always a barrier that goes down (and therefore an enhancement at energies below the barrier) resulting in a much smaller enhancement as that for positive Q -value channels.

A picture similar to the coupled channel description is obtained if the internal degrees of freedom are described by a harmonic oscillator in which the mean excitation energy $\langle \epsilon_i \rangle$ is sufficiently small that

$$\langle \epsilon_i \rangle \ll \hbar \omega \quad 60$$

where ω is the Hill-Wheeler frequency, the weighting function in eq.56 is a Gaussian³⁰⁻³¹. For most fusion reaction which involve intermediate-mass heavy ion the condition expressed by eq.60 is well satisfied for excitations of the order of $\langle \epsilon_i \rangle < 2$ MeV. This fact suggests that in order to obtain a general parametrization to fit the fusion cross sections²⁰ a truncated barrier fluctuation can be introduced by allowing a variation of the surface-to-surface distance (s), analogous to that what is assumed in the zero-point-motion picture³²⁻³⁴, through the s -dependent transmission coefficients $T_L(E, s)$

$$T_L(E) = \frac{1}{\sqrt{2\pi} \sigma^2} \int_{-t\sigma}^{+t\sigma} ds \, T_L(E, s) \exp\left[-\frac{s^2}{2\sigma^2}\right] \quad 61$$

where t is a truncation parameter suggested by Reisdorf et al.³⁵ taking into account a limited strength of coupling interactions of the system and their finite excitation energy.

A fluctuating distance s of the nuclear surfaces is equivalent to a fluctuating barrier height. The gauss function in eq.61 replaces the weights $|U_{m0}|^2$ of the

coupled channel picture.

The importance of the truncated barrier fluctuation formalism lies in the fact that it provides a simple parametrization of experimental sub-barrier fusion cross sections.

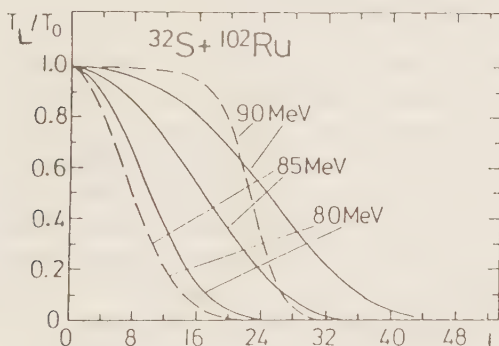


Fig.15: Normalized transmission coefficients as calculated with eq.61 with (full line) and without (dashed) fluctuating barrier.

The truncated barrier fluctuation picture as well as the coupled channel mechanism predict a larger mean angular momentum for the compound nucleus formation especially near the barrier. At low energies the transmission coefficients decay exponentially with energy for all partial waves and the mean angular momentum for the compound nucleus formation converges to a finite value as is shown in fig.15. More detailed consideration on the expected total angular momentum due to coupling effects in a compound nucleus is presented in sec.7.4.

3.3 PROXIMITY POTENTIAL

The variety of theoretical nuclear potentials that have been developed to describe elastic scattering cross sections were also employed in calculations to account for the sub-barrier fusion enhancement.

The most critical approximation entering into expressions for these potentials is the adiabatic or frozen density and frozen shape approximation which does not exactly account for nuclear density saturation and shape distortions in the overlap region or of the whole nuclei. Therefore, when these potentials are used to predict fusion cross sections, in particular at sub-coulomb energies, they become unphysical in the overlap region and a phenomenological extension becomes necessary.

The PROXIMITY POTENTIAL³⁶ arises from a generalization of the 'proximity theorem'³⁷, according to which the force between two gently curved objects in close proximity is proportional to the potential per unit area between flat surfaces made of the same material, the constant of proportionality being a measure of the mean curvature of the two objects within the region of mutual approach.

At first the interaction energy per unit area, $e(s)$, is calculated for two semi-infinite slabs of matter at distance ' s '. When the surfaces are diffuse this separation is calculated at half-max density.

The adequacy of this model rests on the fact that the surface diffuseness of nuclei is much smaller than their radius which implies that the nuclear surfaces seem infinite on a scale of this diffuseness. Employing a Fermi distribution for both the matter density profile as well as

the microscopic nucleon-nucleon potential the result ' $e(\xi)$ ' is integrated over these surfaces, leading to

$$V_N(\xi) = 4\pi \gamma b \bar{R} \Phi(\xi) \quad (62)$$

where $\bar{R} = \frac{C_1 C_2}{(C_1 + C_2)}$, C_i : nuclear radii 63

Evaluation of the proximity potential is done by selecting either the universal proximity function tabulated by Blocki et al.³⁶, $\Phi_T(\xi)$, or the following analytic expressions which are represented in fig.16.

$$\Phi_A(\xi) = -0.5(\xi - 2.54)^2 - 0.0852(\xi - 2.54)^3, \xi \leq 1.2511 \quad (64)$$

$$\Phi_A(\xi) = -3.437 \exp(-\xi/0.75), \xi \geq 1.2511 \quad (65)$$

where

$$C_i = R_i \left(1 - b^2/R^2 + \dots \right) \quad i = 1, 2 \quad (66)$$

$$\xi = (r - C_1 - C_2)/b \quad (67)$$

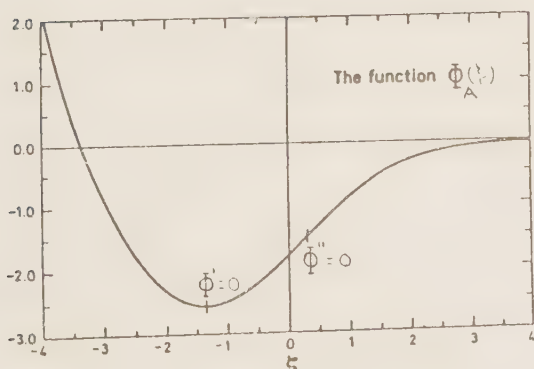


Fig.16: The function $\Phi_A(\xi)$ describing the shape of the proximity potential.

The quantity R is the equivalent sharp-surface radius, b is related to the surface diffuseness and γ is the surface energy. For these parameters the recommended values are:

$$R = 1.28 A^{1/3} - 0.76 + 0.8 A^{-1/3} \text{ fm} \quad 68$$

$$b = 1.0 \text{ fm} \quad 69$$

$$\gamma = 0.9517 \left[1 - 1.7826 \left(\frac{N-Z}{A} \right)^2 \right] \text{ MeV} \quad 70$$

In order to remove violation of the saturation of nuclear density for $\xi < 0$, a phenomenological modification for $\xi \leq 0$ was proposed by Randrup³⁸. This is given by

$$V_N(\xi) = 4\pi\gamma b \bar{R} \Phi(\xi=0) + 4\pi\gamma b \bar{R} \xi \quad 71$$

4. EXPERIMENTAL SET-UP

4.1 PRINCIPLE OF THE MEASUREMENT

Among the various products of a typical fusion reaction one can find in a time sequence at first the evaporated neutrons, protons, alpha-particles and their corresponding evaporation residues.

After the particle evaporations the cascades of gamma rays take place, and when the evaporation residues have already recoiled out of the target the final stages of the gamma ray cascades are still observed. (fig.5 Kapitel 2)

The detection of the evaporation residues, which for heavier systems increasingly concentrate into a narrow cone around the beam axis, is carried out with in a huge background, suggesting a special measurement set-up.

One experimental method to discriminate between fusion events and beam-like background is using a Wien filter^{39,40} which is sensitive to the differences in velocities between the beam-like ions and evaporative recoils.

Due to the differences of the ratio of kinetic energy to ion charge, the discrimination between fusion events and beam-like background has been done also successfully employing electrostatic deflectors⁴¹.

Finally the evaporation residue yield and angular distribution can be measured (outside the central core which is dominated by the projectiles) by means of their time of flight against a pulsed beam, with a multi-ring parallel-plate avalanche counter (MPAC).

For the systems of our interest the predicted fission barrier employing the liquid drop model is about 40 MeV. The competition between fission and particle evaporation for these systems is shown in fig.17.

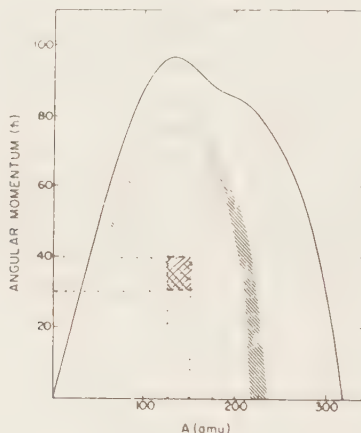


Fig.17: The critical angular momentum ℓ_{cr}^f for the vanishing of the fission barrier as a function of mass number. The solid line gives the value of angular momentum at which the fission barrier of β -stable nucleus of mass A is predicted to vanish. The hatched region corresponds to values where the binding energy of neutrons becomes equal to the fission barrier. (From Plasil et al.⁴²). The double hatched area corresponds to the angular momentum of compound nuclei expected in these measurements.

The fig.17 demonstrates that the fission is negligible which is in agreement with the experimental data ²⁰.

It is also important to note that the sum over the cross sections of all exit channels is clearly dominated by the elastic scattering. Such dominance appears quantitatively by many orders of magnitude when compared to the fusion cross section. Therefore it is expected that within the angular range spanned by the kinematic angular spread of the recoil nuclei, the differential cross section of the Rutherford scattering is also many orders of magnitude larger than the differential fusion cross section. According to fig.18 the ratio between the Rutherford scattering and fusion events in the angular range spanned by the kinematic angular spread of the evaporation residues is higher than 10^5 .

In order to get a reasonable counting rate of the fusion products a detector had to be developed to operate with a typical intensity of S-ion beams of $\ln A$ (electric) leading to a total elastic scattering counting rate of about 1 MHz. The data acquisition system is not able to sustain very high counting rates (400kHz), therefore, the signals from elastically scattered projectiles had to be partly suppressed by electronic methods.

The best detector for high counting rates and a large detection area is a parallel plate avalanche counter. It allows fast timing and can be used within a multi-ring 2π -azimuthal geometry. The experimental set-up is schematically shown in fig.19.

The multi-ring parallel-plate avalanche counter (MPAC) was centered at 0° , at 560 mm from the target, in the plane perpendicular to the beam direction. A Ta shield covering angles $1.0^\circ < \theta_L < 3.0^\circ$ was located in front of the detector in order to reduce the huge counting rate due to elastic scattering at very small angles. Therefore the MPAC covers the angular range $3.0^\circ < \theta_L < 11.0^\circ$.

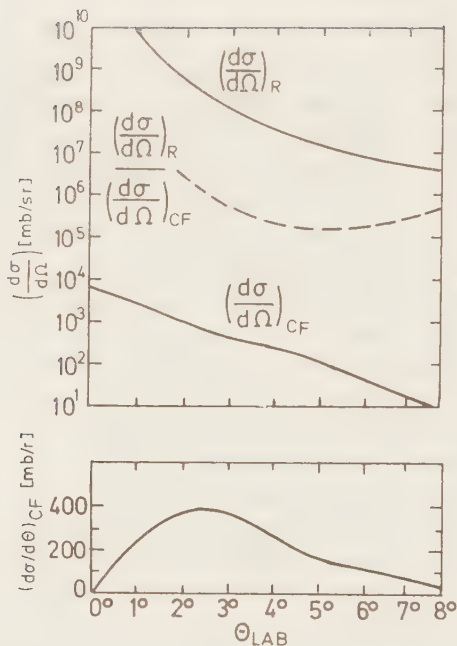


Fig.18: Comparison between the Rutherford scattering and total fusion cross section for the system $^{32}\text{S} + ^{104}\text{Ru}$ at $E_{\text{lab}} = 120\text{MeV}$. The magnitude of the fusion cross section and the relative intensities of $(n,n\dots)$ -, $(p,n\dots)$ -, $(p,p,n\dots)$ - and $(\alpha,n\dots)$ -evaporation were obtained from ref. (20).

The projectile beams were collimated by a pair of well aligned slits located at 20 and 30 mm up-stream from the target having circular apertures of 6 and 5 mm, respectively.

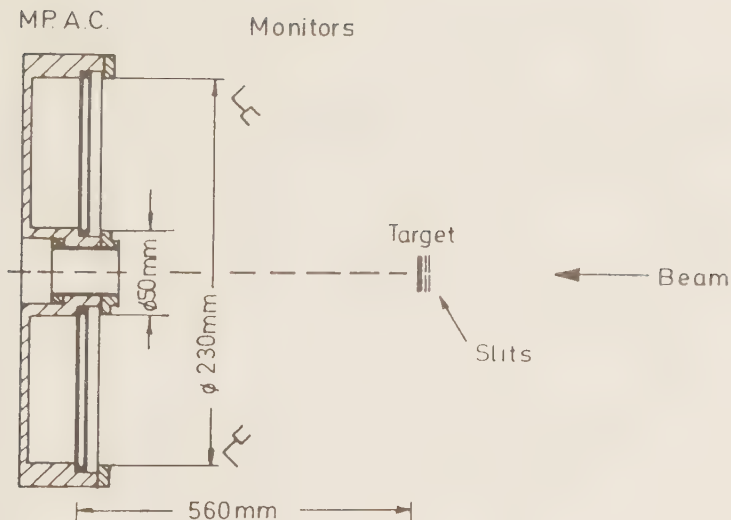


Fig.19: Schematic drawing of the experimental set-up for the near-barrier angular distributions of even S-ions on Mo, Ru, Rh and Pd isotopes.

The dimensions of the slits provide a good shadow on the detector in order to avoid background in the time-of-flight spectrum due to edge scattering.

Two solid state counters have been mounted symmetrically down-stream from the target at an angle of 9.3° , each of them covering a solid angle of 2.3×10^{-5} sr. They served as beam intensity monitors.

Employing the experimental set-up illustrated in fig.19 the angular distributions of 30 projectile-target combinations: $^{32,36}\text{S} + ^{92,94,96,98,100}\text{Mo}$, $^{100,101,102,104}\text{Ru}$, ^{103}Rh , $^{104,105,106,108,110}\text{Pd}$ have been measured at $E_{\text{lab}} = 120$ MeV and for some systems at $E_{\text{lab}} = 114$ MeV. The principal characteristics of the targets are shown in Table 1.

Target	Isotope							Thickness ($\mu\text{g}/\text{cm}^2$) on $\sim 20 \mu\text{g}/\text{cm}^2 \text{ C}$
	96	98	99	100	101	102	104	
^{106}Ru	0.1	0.1	0.1	0.1	0.2	1.2	98.5	123
^{102}Ru	0.1	0.1	0.1	0.3	0.5	98.7	0.5	80
^{101}Ru	0.1	0.1	0.3	0.5	92.7	6.0	0.4	106
^{100}Ru	0.1	0.1	1.3	92.9	3.6	1.9	0.2	103
	92	94	95	96	97	98	100	
^{100}Mo	0.53	0.18	0.29	0.34	0.28	0.96	97.42	76
^{98}Mo	0.32	0.22	0.45	0.59	0.69	97.18	0.55	93
^{96}Mo	0.98	0.24	1.01	95.9	1.0	1.32	0.25	100
^{94}Mo	1.31	88.2	5.09	2.15	0.79	1.82	0.64	103
^{92}Mo	98.27	0.46	0.37	0.26	0.13	0.27	0.25	92
	102	104	105	106	108	110		
^{110}Pd	0.01	0.12	0.36	0.46	1.32	97.73		93
^{108}Pd	0.01	0.07	0.27	0.95	98.35	0.36		75
^{106}Pd	0.02	0.13	0.79	98.48	0.48	0.12		94
^{105}Pd	0.01	0.44	97.38	1.72	0.35	0.11		90
^{104}Pd	0.15	95.25	2.64	1.23	0.54	0.19		92
^{103}Rh	100							178

Table 1.: List of the targets used to measure the angular distributions with their relative isotopic enrichment (in %).

For all target-projectile combinations the discrimination between the evaporation residues and the elastically scattered projectiles has been done by time-of-flight against the pulsed beam provided by the Tandem at the Munich accelerator laboratory.

The one-dimensional TOF spectrum which is shown in fig.20 identifies clearly and unambiguously the evaporation residue events. The time-of-flight differences for the evaporation residues and recoil target nuclei in respect to the elastic scattered projectile are about 72 and 46 ns,

respectively. These intervals are large compared to the time resolution in the TOF-spectrum of 6ns FWHM. Nevertheless, due to their extremely large intensity the elastic scattered events extend a tail towards the fusion products and a careful background correction was necessary. The target recoils vanished within this tail.

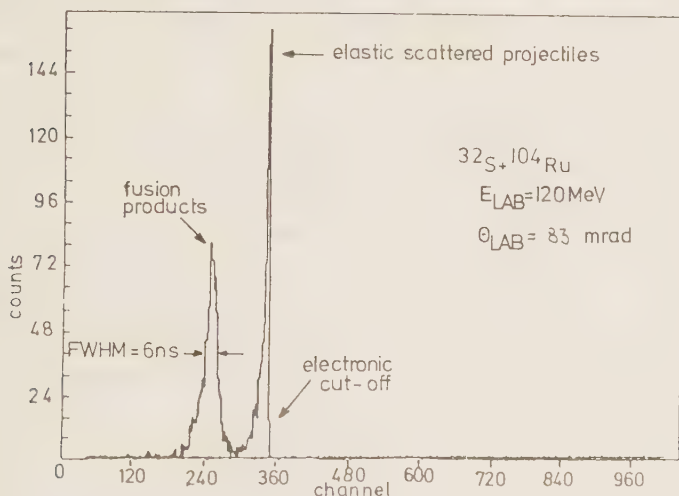


Fig.20: Time-of-flight spectrum for $^{32}\text{S} + ^{104}\text{Ru}$ at incident energy $E_{\text{lab}} = 120 \text{ MeV}$.

The low-energy chopper-buncher of the pulsed beam system was operated with a time resolution of $\sim 2 \text{ ns}$ and a repetition interval of 400 ns . The main contribution to the total time resolution of 6 ns was therefore due to the detector itself.

4.2 MULTI-RING PARALLEL-PLATE AVALANCHE COUNTER

A parallel-plate avalanche counter (MPAC) (see fig.21) consists basically of two plane electrodes delimiting a sensitive volume in which gas amplification takes place. The gas amplification is made by applying an electric field to the electrodes.

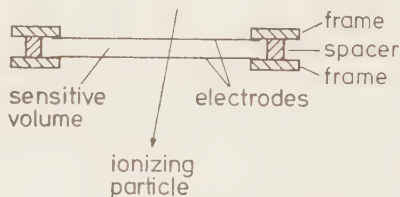


Fig.21: Schematic drawing of an avalanche counter of parallel electrodes.

The passage of an ionizing particle through the sensitive volume produces a track of primary electron-ion pairs. The electrons drift towards the anode starting avalanches of electrons along the drift path.

Detectors of this kind were originally employed for the detection of low ionizing particles like photons, electrons, alpha-particles⁴³⁻⁴⁵ and later were recognized to be an excellent tool for heavy ions since they produce more primary electrons giving rise to a large output signal even at low pressures (~1mbar). According to Breskin et al.⁴⁶ low pressure chambers are well suited for very fast timing measurements of heavy ions.

A detector with planar geometry and a homogeneous field must be chosen and operated in a high gas-multiplication regime to provide a sufficiently high output signal at a

given primary ionization and hence a good signal-to-noise ratio.

The gas-filled proportional counters overcome the disadvantages of solid state detectors which are limited by radiation damage and do not allow very high counting rates⁴⁷.

Detectors of this kind are usually filled with pure hydrocarbons like butane, butylen, pentane, heptane, isobutane etc, or with organic vapours like methylal, acetone etc. A gas with self photon quenching properties is very suited.

Such avalanche counters with sensitive areas of up to several hundred cm^2 can be operated in heavy ion measurements⁴⁸ and can support very high counting rates ($10^6 - 10^7$ particles/s)⁴⁹. Their good time-resolution, their 100% detection efficiency, their simple construction and their insensitivity to radiation damage makes them very well suited for time measurements in heavy ion reactions involving large solid angles.

In the homogenous electric field secondary ionization sets in immediately and an avalanche of the Townsend type will be formed.

The final number N of electrons, due to this process, is given by

$$N = \int_0^d N_0(x) \exp(\alpha x) dx \quad 72$$

where

$N_0(x)$ is the number of primary electrons/cm,

d is the drift path,

α is the first Townsend coefficient,

and N is the final number of secondary electrons.

The coefficient α is the mean ionization probability per unit path length and is related to the reduced field strength E/p (E is the electric field strength between the electrodes and p is the gas pressure of the sensitive volume), according to the following equation⁵⁰

$$\alpha/p = A \exp \left\{ -B/(E/p) \right\} \quad 73$$

where A and B are the gas-specific constants. For isobutane, which was used in this study, it is found⁵¹ $A=18/(\text{cm mbar})$ and $B=315 \text{ V}/(\text{cm mbar})$

The output signal observed with a high-impedance pre-amplifier, exhibits a fast rising component produced by electrons from the ionization process and a much slower component due to the corresponding positive ions.

The rise time T_e of the electronic component of the signal is obtained approximately by the drift time of the corresponding electrons across the last mean ionization length $1/\alpha$,

$$T_e = \frac{1/\alpha}{v_e} \quad 74$$

where v_e is the drift velocity of the electrons. Correspondingly, the rise time of the slow signal component is inversely proportional to the drift velocity of the positive ion.

Taking into account that the charge which is induced on the electrodes is proportional to the drift path and most electrons drift across the length $1/\alpha$ whereas the positive ions cross nearly the total gap d , the slow signal is a factor of αd higher than the fast one

$$\frac{Q_{\text{ion}}}{Q_{\text{electr.}}} \sim \frac{\delta}{1/\alpha}$$

75

For time measurements only the fast component is used, which is of the order of some mV, requiring an amplification by a factor of ~200 in order to provide signals for further processing in a constant-fraction discriminator.

The MPAC (fig.22), similar to that of L.Muller⁵², has been developed in a ring geometry in order to get maximum counting rates in angular distribution measurements near 0°. A hole in the center is provided to allow the passage of the beam. The active area is limited by an outer and inner diameter of 230 and 50 mm, respectively.

The cathode and anode are maintained at a fixed distance by means of outer and inner ring spacers and are mounted in a thick aluminum ring module.

The cathode consists of a stainless steel mesh grid (mesh size: 0.25 mm²) with a transparency of 91%. Its contact to the power supply has been made all around the frame, by means of a copper layer on the outer spacer.

The grid was chosen instead of a foil, which normally provides a more homogeneous field, because damages produced by discharges leads to gas leakage in the case the foil serves as electrode as well as pressure foil. Besides that it is difficult to provide a homogeneous field because the electrode is bowed by the gas pressure and the gas amplification is very sensitive to the distance of the electrodes.

A two foil arrangement avoiding these difficulties (pressure-foil and electrode-foil separated) is not suited for our case. The energy of the evaporation residues (~30 MeV) is not large enough in comparison with the energy loss in the foils⁵³ (~12 MeV).

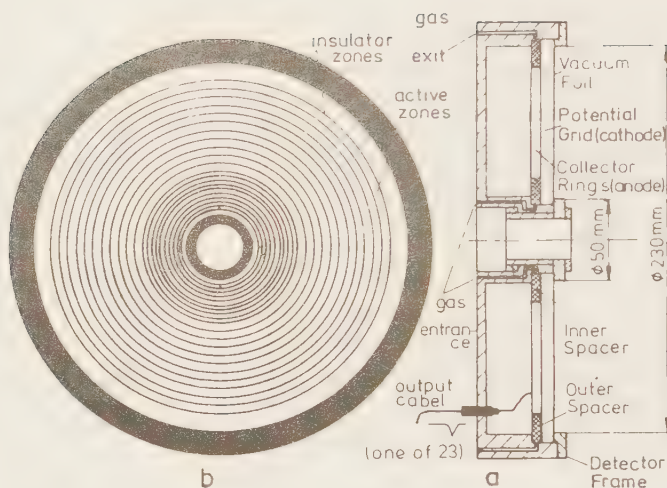


Fig.22: Schematic view of the position sensitive MPAC a) and its collector rings b).

The vacuum (particle entrance) window consists of a hostaphan foil with a thickness of about $300\text{ }\mu\text{g}/\text{cm}^2$.

The anode is made up of a metallized epoxi resin plate currently used for printed boards. The active zones are composed by a copper layer of $\sim 500\text{ }\mu\text{g}/\text{cm}^2$ covered by a platinum layer of $\sim 300\text{ }\mu\text{g}/\text{cm}^2$ and are contacted at the back side to the output cables.

The active zones are made up of twentytwo concentric rings in order to subdivide the zenithal angular range. The inner and outer rings are 3 and 5 mm wide, respectively, providing better angular resolution at small angles and reduction of high counting rates of the elastically scattered particles. The rings are separated by an insulator zone which is 0.3 mm wide.

Generally a MPAC whose sensitive volume is at a pressure in the range of 1-10 mbar has a performance very sensitive to the nature of electrodes and the distance between them. In order to optimize our detector we have choosen a fixed pressure of 6 mbar in its test as well as in the measurements.

The detector was tested with 5.5 MeV alpha-particles from a ^{241}Am source. For different gaps of 2, 4 and 6 mm the reduced field strenght was varied in the range from 100 to 140 V/cm mbar.

A mesh produces inhomogeneties in the electric field, resulting in a lower gas amplification than in MPAC-foil counters. The lower amplification effect due to inhomogenities becomes more serious for smaller gap distances (see fig.23.a). Therefore we have choosen in the experiment a gap distance of 6 mm, where the time resolution(~ 4 ns) is still good and the gas amplification(an anode signal height about 1 mV was measured) is much higher than for small gap distances, due to more primary electrons(at constant pressure) and high E/p values(the maximum electric field without accidental sparks is larger for the 6mm gap).

Since the experiment requires low background because of the expected low intensity of the evaporation residues to be detected, the number of accidental sparks has to be reduced greatly. The 6mm gap meets this requirement much better than 4 or 2 mm gap.

The calculated gas amplification with eq.73 for 6 mm and 4 mm gap at 6 mbar pressure is shown in fig.23.b The calculated amplification as a function of E/p shows qualitatively agreement with the measured one. However differences exist. The slope of the calculated amplification is steeper. This fact can be explained as due to the inhomogeneous field arising from the mesh geometry resulting

in an average gas amplification smaller than that corresponding to parallel foils.

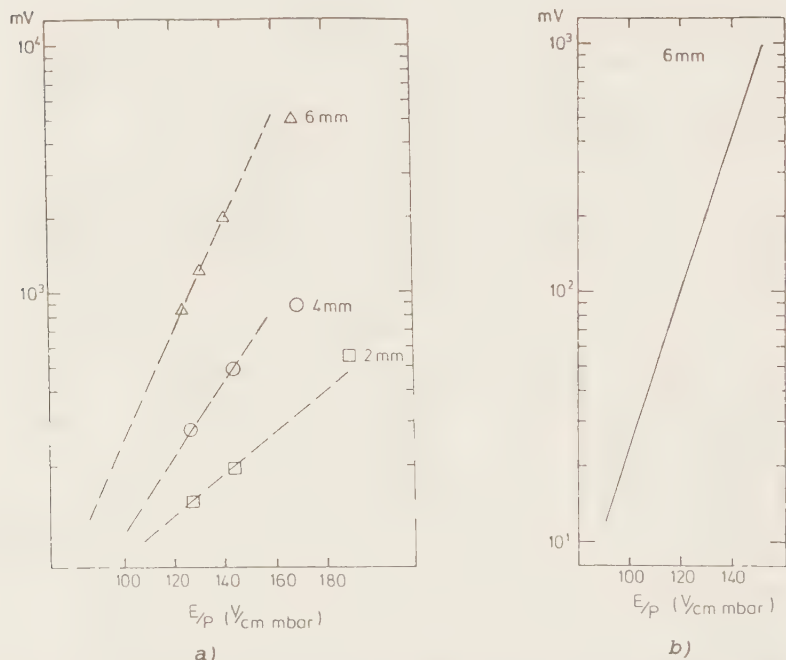


Fig.23: a) Measured (electronic amplification of about 250) and calculated b) gas amplification for the MPAC.

In addition the absolute value of the calculated amplification is a factor of 5-10 higher than the measured one. This discrepancy may be explained by an underestimation of the capacity of the detector (feedthrough neglected) and uncertainties of the parameters A and B, which were determined empirically at a very homogeneous electric field.

Due to a limited number(11) of inputs for the pseudo-ADC and in order to span continuously the angular range from 3 to 11 degrees several rings were combined with their neighbouring ones leading to the following mean

zenithal and solid angles in laboratory system as shown in table 2.

j Position	θ_{LAB} (mrad)	solid angle (10^{-3} sr)
2	52	1.77
3	58	1.95
4	63	2.13
5	68	2.34
6	75	2.54
7	83	5.61
8	94	6.31
9	109	11.63
10	127	14.13
11	146	16.07
12	176	9.66

Table 2: Summary of averaged zenithal and associated solid angles in the laboratory system disposed in a 2π -azimuthal geometry of the ring detector at 0° around the beam (see Fig.19).

For the geometry depicted in fig.19 an angular resolution of 0.2 and 0.4 degrees is obtained for the inner and outer rings of the detector, respectively.

In order to use the ring detector at first its operational conditions, as gas pressure and flow and high voltage, are adjusted to support high counting rate and later the electronic set-up is employed to select the fusion events and cut off substantially the elastic scattering events. When the maximal voltage is reached for a certain pressure, care has to be taken with the gas flow in order to avoid local pressure variations which could result in

electrical discharges.

The gas was provided radially flowing from 4 circular apertures with a diameter of 4mm at the inner spacer between anode and cathode grid to similar apertures in the outer spacer. The region of highest counting rate near the inner spacer is hereby kept at a maximum gas exchange rate.

The gas was allowed to circulate behind the anode by means of circular apertures in the outer insulator zone in order to increase the total gas volume inside the detector (not the sensitive volume), decreasing, consequently, the chances of turbulated flows. A typical gas flow was about of 20 cm³/s.

The main operational characteristics of the MPAC are resumed in Table 3.

Thickness of vacuum foil	300 $\mu\text{g}/\text{cm}^2$
Counter gas	iso-butane i(C ₄ H ₁₀)
Operational pressure	6 mbar
Distance between electrodes	6 mm
Operational voltage	460 V
Angular range spanned by the detector in L-system.	3.0° - 11.0°
Reduced field strength	127 V/ cm mbar

Table 3: Specification data of the multi-ring parallel-plate avalanche counter(MPAC).

4.3 ELECTRONIC SET-UP

The electronic set-up employed in this work is illustrated by the block diagram in fig.24.

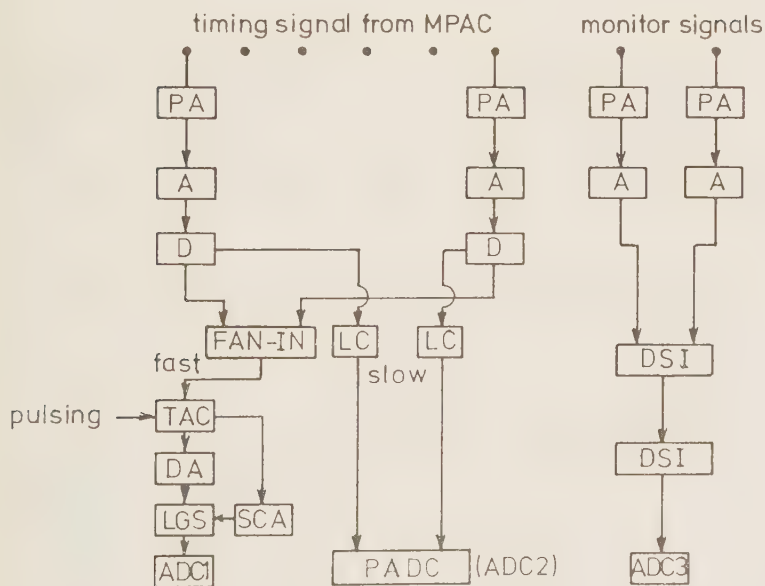


Fig.24: Schematic diagram for the electronic set-up used in this work. PA =fast pre-amplifier (development of W. Wagner, TU-Munchen), A =fast amplifier (FTA 410 L-ESN), D =discriminator (621BL-Lecroy), TAC =time-to-amplitude converter (437A-Ortec), DA =delay amplifier (427A-Ortec), SCA =single channel analyzer (406A-Ortec), LGS =linear gate stretcher (442-Ortec), PADC =pseudo-ADC, DSI=dual sum and invert (433A-Ortec) and LC = level converter NIM to TTL (K 1200).

All output timing signals from the anode rings have been sent through a fast pre-amplifier and amplifier to a snap-off timing discriminator. The fast output signals from these discriminators were processed in a logic fan-in to provide only one START signal for the time-to-amplitude converter TAC which measures the time-of-flight against the pulsed beam.

The elastic scattering events registered in the time-of-flight spectrum were mostly suppressed in the linear gate stretcher setting an upper limit for the TAC output signals below the elastic scattering events. A typical suppression factor for the elastic scattering events was about 10^{-3} .

The energy loss in the sensitive volume is about 4 times higher for the fusion products than for the elastic scattered particles. The best setting for the discriminator threshold is one where the elastically scattered events are suppressed as highly as possible and all compound events lie above the threshold. In order to find this setting we measure the efficiency for compound events and elastic events as a function of the MPAC voltage. One result of this measurements is shown in fig.25. The detector voltage (460 V), used to measure the angular distribution, insures that most of the compound nucleus events were registered.

To distinguish between each ring of the detector the slow output signals from the discriminator were fed into a device with 12 digital inputs that we call pseudo-ADC (PADC). This device instead of the ADC transmits a 12 bit wide pattern corresponding to the combination of the input pulses to the computer interface. In a spectrum produced by the PADC the rings show up as channel numbers that are a power of 2.

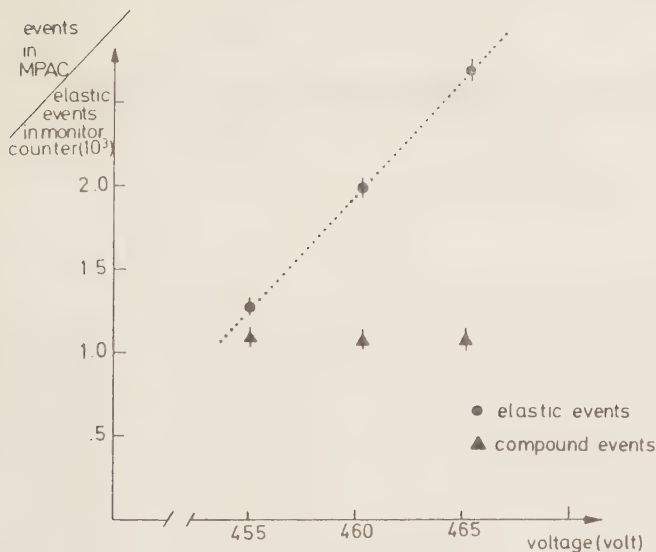


Fig.25: Graphic representation for the determination of the the optimum setting of the discriminator thresholds for a ring.

Crosstalk and pile-up effects between rings, which means that more than one discriminator has fired, appear as a channel number corresponding to the combination of such ring channels.

The measurement showed crosstalk rates between neighbouring rings up to 5%. In the data analysis half of these events were assigned to each ring.

The heights of the pulses arising from the detector were not measured because the discrimination between the elastically scattered particles and evaporation residues could be achieved by means of the time-of-flight spectra.

The measurement of pulse heights would require a fast charge sensitive device which is capable to integrate such short signals (with width of about 10 ns) with sufficient precision.

5. ANALYSIS OF THE EXPERIMENTAL DATA

5.1 GENERAL REMARKS

The total detection efficiency of the Munich recoil spectrometer depends on the relative intensity of evaporation residues from the compound nucleus formation. These relative intensities of the evaporation residues were originally obtained from their velocity distributions²⁰ as determined within the recoil spectrometer and measured in the angular range of 0° to 1.8° in the laboratory system. A disadvantage of this method lies on the fact that the heavier evaporated particles, particularly the alpha-particles, produce a kinematic angular spread which is not well covered by the acceptance of the recoil spectrometer (see fig.4). Therefore, in this work the relative intensities of evaporation residues associated with large kinematic angular spread were obtained by means of their angular distribution, which were measured with the MPAC.

The two different methods to determine relative intensities are described in the next sections.

Since the recoil spectrometer has its maximum efficiency for (n,n...) evaporation residues, while the MPAC allows to detect the (α ,n...) residues best, the absolute fusion cross sections (or equivalently the total detection efficiency of the recoil spectrometer) was finally obtained by combining the counting rates of both instruments in an iteration procedure as explained below.

5.2 DESCRIPTION OF DATA EVALUATION WITH THE MUNICH HEAVY-ION RECOIL SPECTROMETER

The total angular distribution of the residual nuclei can be reconstructed from the fractions of the most important types of evaporation process that take place after the compound nuclei formation. The residual nuclei are formed at the target position and recoil at least partly into the entrance aperture of the recoil spectrometer.

Assuming that the yield of sub-coulomb fusion can be reproduced summing over n different types of residual nuclei one can express the bulk of the total residue nuclei produced at the target position as

$$Z = \sum_{i=1}^n Z_i \quad 76$$

where Z_i is the bulk of residue nuclei due to the evaporation channel of the type i . For each evaporation channel of the type i , the corresponding residual nuclei N_i which are focused by the recoil spectrometer on the detector system being identified with an efficiency ϵ_i are given by

$$N_i = \epsilon_i Z_i \quad 77$$

If the total number of recoil nuclei N associated with a reaction is detected in the same way with an efficiency ϵ , it results that

$$N = \epsilon Z \quad 78$$

Using the eqs.77-78 one can write that for a certain evaporation channel i , the relative intensity of detected

recoil nuclei ($\alpha_i = N_i / N$) can be written as

$$\alpha_i = \frac{\dot{\epsilon}_i}{\epsilon} \bar{\alpha}_i \quad 79$$

where $\bar{\alpha}_i = Z_i / Z$ is the probability for an evaporation channel of the type i at the target.

Combining eq.79 with the unitary property for the summation of α_i and $\bar{\alpha}_i$ over i , results that

$$\epsilon = \sum \bar{\alpha}_i \epsilon_i \quad 80$$

or

$$1/\epsilon = \sum \alpha_i / \epsilon_i \quad 81$$

The evaluation of any ϵ_i can be obtained by a simulation employing a Monte Carlo program called TRANMI¹⁸.

Regarding the statement related to the eq.76, the total fusion cross section can be expressed by

$$\sigma_f = \sum_{i=1}^n \int_0^{2\pi} \int_0^{\theta_r} \left(\frac{d\sigma}{d\Omega} \right)_i \sin \theta \, d\theta \, d\varphi \quad 82$$

where

$\left(\frac{d\sigma}{d\Omega} \right)_i$ is the differential fusion cross section of the evaporation channel i in the L-system.

φ and θ are the azimuthal and the zenithal angle relative to the beam direction, respectively (L-system).

The differential fusion cross sections for the residual nuclei can also be simulated for each type of evaporation process i , employing again the Monte-Carlo program TRANMI.

In such a simulation, neutrons, protons and alpha-particles are assumed to evaporate with a given anisotropy in the CM-system. Details for such simulations

are described in sec.7.4.

For each zenithal angle θ , in the L-system, the simulated differential fusion cross sections $d\sigma_i/d\Omega$ are proportional to the measured one as follows

$$\frac{d\sigma}{d\Omega} = C \sum \bar{\alpha}_i \frac{d\sigma_i}{d\Omega} \quad 83$$

with

$$\int \left(\frac{d\sigma_i}{d\Omega} \right) d\Omega = n_i \quad 84$$

being the number of cases employed in the Monte-Carlo program.

Regarding eq.82, the partial fusion cross section associated with an evaporation channel i can be expressed as

$$\sigma_f^i = \bar{\alpha}_i \sigma_f. \quad 85$$

Expressing σ_f^i and σ_f by the differential cross section in eq.83 one obtains

$$\sigma_f = C \sum \bar{\alpha}_i n_i \quad 86$$

or, if $n_i = n$ for all i ,

$$C = \sigma_f / n \quad 87$$

Generally fusion cross sections are obtained from fusion residue counting rates by a normalization to the Rutherford cross section employing a monitor counter for elastically scattered projectiles,

$$\sigma_f = \frac{1}{\epsilon} \sigma_M \frac{N_c}{N_M} \quad 88$$

where

σ_M is the differential Rutherford cross section

at the angle θ_M of the monitor counters times their solid angle, i.e.

$$G_M = \frac{dG_R(\theta_M)}{d\Omega} \Delta\Omega_M \quad 89$$

N_C is the number of evaporation residues which are detected, and

N_M is the mean value of the Rutherford scattered particles detected by the monitor counters.

The total detection efficiency of this instrument is determined by the expression

$$\epsilon = f_d f_c T a(\theta_I) \quad 90$$

where

f_d is the transmission associated to the recoil transport through the various supporting grids.

f_c is the detection efficiency of the channel-plate.

T is the transmission of the recoils under the influence of the focusing and deflecting fields and the various beam defining apertures of the recoil spectrometer.

$a(\theta_I)$ is the fraction of the recoils that are accepted through the entrance aperture.

Before the recoil nuclei have been transported under the influence of the focusing and deflecting fields their bulk is reduced by the factor $a(\theta_I)$.

For a target-entrance aperture geometry, the fraction of the measured cross sections can evaluate the acceptance

of the recoil spectrometer as follows

$$a(\theta_I) = \frac{1}{\sigma_f} \int_0^{2\pi} \int_0^{\theta_I} \left(\frac{d\sigma}{d\Omega} \right) \sin\theta d\theta d\varphi \quad 91$$

Using the eqs.83,87 the acceptance expressed by eq.91 can be written as

$$a(\theta_I) = \sum \bar{\alpha}_i \int_0^{2\pi} \int_0^{\theta_I} \left(\frac{1}{n} \left(\frac{dn_i}{d\Omega} \right) \right) \sin\theta d\theta d\varphi \quad 92$$

From eq.92 can be suggested that the fractional acceptance v_i for a certain type of residual nuclei, can be written as

$$v_i = \frac{1}{n} \int_0^{2\pi} \int_0^{\theta_I} \left(\frac{dn_i}{d\Omega} \right) \sin\theta d\theta d\varphi \quad 93$$

Combining eqs.92,93 with eq.91, the acceptance can be expressed as

$$a(\theta_I) = \sum v_i \bar{\alpha}_i \quad 94$$

With the purpose to give an additional information on the angular distribution measured with the MPAC, an evaluation for an averaged differential fusion cross section over the acceptance angle θ_I , can be given by

$$\left(\frac{d\sigma}{d\Omega} \right)_{0^\circ} = \frac{1}{\Delta\Omega_{RS}} \int_0^{2\pi} \int_0^{\theta_I} \left(\frac{d\sigma}{d\Omega} \right) d\Omega \quad 95$$

where $\Delta\Omega_{RS}$ is the solid angle determined by the entrance aperture .

Due to the small magnitude of the angle θ_I , the solid angle $\Delta\Omega_{RS}$ can be approximately given by

$$\Delta \Omega_{R_0} = \int_0^{2\pi} \int_0^{\Theta_I} \sin \theta \, d\theta \, d\varphi \approx \pi \Theta_I^2 \quad 96$$

Combining the eqs.95,96 with eq.83 one can write that

$$\left(\frac{d\sigma}{d\Omega} \right)_0 = \frac{1}{f_d f_c \bar{T}} \frac{\sigma_M}{\pi \Theta_I^2} \frac{N_c}{N_M} \quad 97$$

where

$$\bar{T} = \frac{\sum \bar{\alpha}_i \varepsilon_i}{\sum \bar{\alpha}_i v_i} = \frac{\varepsilon}{a(\Theta_I)} \quad 98$$

In a plane $d\sigma/d\Omega$ versus θ , the abscissa related to this averaged differential cross section can be written as

$$\Theta_m = \frac{\int_0^{\Theta_I} \theta \left(\frac{d\sigma}{d\Omega} \right) d\Omega}{\int_0^{\Theta_I} \left(\frac{d\sigma}{d\Omega} \right) d\Omega} \quad 99$$

The substitution of eq.83 on eq.99 results that

$$\Theta_m = 2\pi \frac{\sum \bar{\alpha}_i v_i'}{\sum \bar{\alpha}_i v_i} \quad 100$$

where

$$v_i' = \frac{1}{n} \int_0^{2\pi} \int_0^{\Theta_I} \theta^2 \left(\frac{dn_i}{d\Omega} \right) d\theta \, d\varphi \quad 101$$

According to eqs.97,100 the near-barrier fusion measurement carried out with the recoil spectrometer leads to an additional information to the present angular distribution measured with the MPAC.

Originally the α_i were evaluated fitting the standard velocity spectra obtained from the Monte Carlo program

TRANMI for each type of evaporation residue to the measured velocity spectrum of the residual nuclei, as obtained from the recoil spectrometer.

The recoil products from the fused system are identified within the recoil spectrometer by means of time-of-flight, energy and energy loss measurements.

The highly isochronous beam transport through the spectrometer allows that the velocity can be determined by time-of-flight, resulting a velocity resolving power of 500-1500 (energy resolution ~0.6%-1.5%, mass resolution ~1-2%).

For all exit channels i a velocity spectrum $h_i(v)$ is simulated with the Monte Carlo code TRANMI, with

$$\int_0^{\infty} h_i(v) dv = h \quad 102$$

where h is the tentative number employed in this simulation. The measured velocity spectrum is denoted by $H(v)$. It is

$$\int_0^{\infty} H(v) dv = N \quad 103$$

where N is the total number of events registered in coincidence by the ionization chamber and channel plate as introduced with eq.78.

The relative yields α_i can be obtained by fitting the simulated velocity spectra to the measured velocity spectrum, according to

$$D \sum_i \alpha_i h_i(v) = H(v) \quad 104$$

where

$$D \alpha_i \int h_i(v) dv = N_i \quad 105$$

is the number of recoil products detected in channel i and D is a normalization factor.

Integrating eq.104 over ν results

$$D \sum \alpha_i \int_0^{\infty} h_i(\nu) d\nu = \int_0^{\infty} H(\nu) d\nu \quad 106$$

Assuming that $\sum \alpha_i = 1$, from eq.106 results

$$D \sum \alpha_i h = N, \quad D = \frac{N}{h} \quad 107$$

The resulting α_i from the fit are used to determine the $\bar{\alpha}_i$, by means of eq.79.

5.3 DESCRIPTION OF DATA EVALUATION WITH THE MULTI-RING PARALLEL-PLATE AVALANCHE COUNTER

To measure the angular distribution with the ring detector there are no crucial restrictions on the acceptance due to the kinematic angular spread of the evaporation residues. Due to this free acceptance the detector efficiency ϵ^R for any evaporation channel is a constant that depends only on the transmission of the cathode grid.

Considering that the recoil nuclei will be detected by the ring detector the eq.77 can get the form for a ring j according to

$$N_j^R = \epsilon^R Z_j^R \quad 108$$

where the quantities referring to this experimental method are denoted with the index R. Following the same statement used for the eq.88 one can write that the number N_i^R of compound events detected in a ring collector j is given by

$$N_j^R = \epsilon^R \frac{N_M}{G_M} \left(\frac{dG}{d\Omega} \right)_j \Delta\Omega_j \quad 109$$

where

N_M is the mean value of the Rutherford scattered particles detected by the monitor counters.

$\left(\frac{dG}{d\Omega} \right)_j$ is the differential fusion cross section related to a ring j in the laboratory-system.

$\Delta\Omega_j$ is the solid angle covered by a ring j
in the laboratory-system

σ_M is the effective Rutherford cross section
at the angle of the monitor positions (see eq.89).

According to eq.109 the registration of the evaporation residues by the MPAC and the mean registration of elastic scattered detected by the monitor counts give rise to the angular distribution by means of the differential fusion cross section.

The differential fusion cross sections are obtained according to eq.109, where ξ^R is 0.91, and a typical N^R is about 10^3 leading to statistical errors about 3%.

5.4 ITERATIVE METHOD TO EVALUATE THE DETECTION EFFICIENCY OF THE MUNICH HEAVY ION RECOIL SPECTROMETER

For the near-coulomb fusion of $^{32,36}\text{S} + \text{A-nuclei}$ of our interest, there is an evidence that the recoil spectrometer can measure accurately the residual nuclei associated with the $(n, n\dots)$ channel and loses gradually this certainty from the $(p, n\dots)$ channel to the $(\alpha, n\dots)$ channel, while for the ring detector occurs the opposite change.

Trying to join the available informations from these instruments in order to get the better evaluation for the efficiency of the recoil spectrometer, the following quantities were obtained by a simulation with the Monte Carlo program TRANMI (in addition to the ξ_i) :

$$v_i = \int_0^{2\pi} \int_0^{\theta_i} f_{\nu}^i(\theta) \sin \theta \, d\theta \, d\varphi \quad 110$$

$$v_i' = \int_0^{2\pi} \int_0^{\theta_i} \theta f_{\nu}^i(\theta) \sin \theta \, d\theta \, d\varphi \quad 111$$

where

$$f_{\nu}^i(\theta) \hat{=} \frac{1}{n} \int \frac{dn_i(\theta)}{d\Omega} \quad 112$$

($n=n_i$ for $i=1\dots 4$ denotes the number of Monte Carlo cases)

For each ring j the following differential cross sections were obtained

$$\frac{d\tilde{\sigma}(\theta_j)}{d\Omega} = \frac{\tilde{\sigma}_M}{\epsilon^R} \frac{N_j^R}{N_M} \frac{1}{\Delta\Omega_j}, \quad j = 2, \dots \quad 113$$

Fitting the standard angular distribution obtained from

a simulation with the Monte Carlo program TRANMI with the measured angular distribution, the first set of relative yields ($\bar{\alpha}_i$) are found. The simulated angular distributions were carried out for the four most abundant exit evaporation channels, i.e. (n,...), (p,n,...), (p,p,n,...), (α ,n,...). It is important to note that for $^{32}\text{S} + ^{92}\text{Mo}$ case the most abundant exit evaporation channels are (n,...), (p,p,n,...), (p,p,p,n,...) and (α ,p,n,...).

Using the above quantities the following iterative routine has been employed:

1. First step

The averaged differential cross section relative to the recoil spectrometer measurements can be evaluated taking into account these initial yields according to eq.97.

$$\left(\frac{d\bar{\sigma}(\theta_m^0)}{d\Omega} \right) = \frac{1}{f_g f_c T^0} \frac{\bar{\sigma}_M}{\pi \Theta_I^2} \frac{N_c}{N_M} \quad 114$$

where

$$T^0 = \frac{\sum \bar{\alpha}_i^0 \epsilon_i}{\sum \bar{\alpha}_i^0 v_i}, \quad \theta_m^0 = 2\pi \frac{\sum \bar{\alpha}_i^0 v_i'}{\sum \bar{\alpha}_i^0 v_i} \quad 115$$

2. Second step

Combining the result from the last step to the angular distribution measured with the ring detector and fitting this composed angular distribution as at the second step, a new set of partial yields $\bar{\alpha}_i^1$ are found.

With the new set of yields ($\bar{\alpha}_i^1$) the detection efficiency of the recoil spectrometer can be found according to eq.80 written in the form

$$\epsilon = \sum \bar{\alpha}_i^k \epsilon_i \quad 116$$

where k is the number of iterations for the iterative process.

A new iteration must be started until a convergent value for this detection efficiency can be found.

5.5 DISCUSSION OF EXPERIMENTAL ERRORS

In order to evaluate the differential cross sections of fusion products care has to be taken with the magnitude of the following errors:

I) Relative errors

The total statistical error is caused by the following quantities :

i) Error of the total elastic scattering events (N_M) which are detected by the monitor detectors.

ii) Error of the total compound formation events (N_J^R) which are detected by the ring detector at each solid angle $\Delta\Omega_j$.

The above errors (i and ii) are minimized by the measurement in a time interval which can provide a good statistic. The typical statistical errors for the elastic scattering events and for the compound formation are about 0.5% and 4% respectively.

II) Absolute errors

The total absolute error is composed by the following quantities :

i) Dead time effect.

- ii) Normalization to the Rutherford cross section.
- iii) Target enrichment.
- iv) Beam profile.

v) Error from the procedure applied to the background subtraction on the total compound formation events registered by the time-of-flight spectra.

The dead time from the TAC was measured in order to evaluate the compound formation events registered in the time-of-flight spectra. A typical magnitude of this dead time was about 40% and it was determined by means of scalers which registered the TRUE START and the TRUE STOP signals from the time-to-amplitude converter (TAC) that measured the time-of-flight. The dead time for any ADC group was the same, therefore its effect was canceled by the Rutherford normalization.

The normalization to the Rutherford cross section is sensitive to the angle that the elastic scattered particles are detected. For the lighter system ($^{32}\text{S} + ^{92}\text{Mo}$) considered in this study the quarterpoint of the angular distribution of elastic scattering particles at $E_{\text{lab}} = 120 \text{ MeV}$ is 119° . Taking into account that the monitor detectors were mounted at 9.3° this error was neglected.

The errors introduced by the isotope enrichment were not taken into account since the abundance of heavier isotope are very reduced as is shown in table 1 and their fusion cross sections are of the same order of magnitude as that for the main isotope, at least at the relative high energies of the angular distribution measurements with the MPAC.

The importance of the beam profile can be considered as

follows:

If the beam is shifted with respect to the geometrical center of the circular line relative to the monitor counters (see fig.26) by a fraction $\delta = \Delta R/R$ of its radius, according to the cosinus law

$$R'^2 = R^2 + (\delta R)^2 + 2 \delta R^2 \cos \varphi \quad (17)$$

where φ is the azimuthal angle around the beam direction.

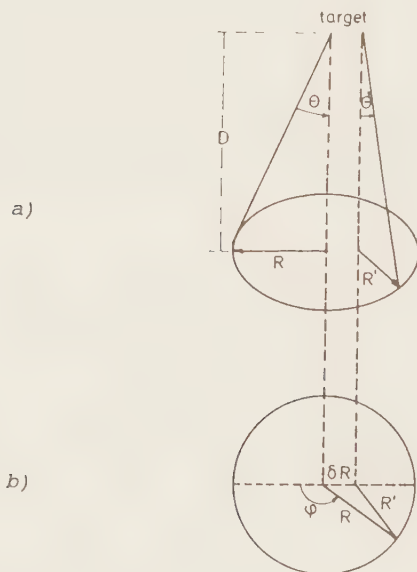


Fig.26: a) Schematic drawing for a beam deviation relative to the center of a circular line on a plane perpendicular to the beam direction containing the monitor counter centers. The distance between the target and the plane containing the monitor counters is D , R is the radial position for the monitor counters. b) Geometrical relation for R and R' .

Dividing eq.117 by D and taking into account that the angular range spanned in this 2π -azimuthal geometry allows the approximation $\tan \theta \sim \theta$, results

$$\Theta'^2 = \Theta^2 [1 + \delta^2 + 2\delta \cos \varphi] \quad 118$$

The total elastic counting ratio associated with the centered and shifted beam are related by

$$N(\Theta') = N(\Theta) \frac{1}{[1 + \delta^2 + 2\delta \cos \varphi]^2} \quad 119$$

Considering that the beam shift is limited by the inner aperture of the iris close to the target results $\delta < 0.05$, therefore the magnitude of this error is $< 1\%$. The error resulting from the monitor positions is expected to be of the same order.

For some time-of-flight spectra (fig.27) a secondary elastic scattered peak was registered. These events were correlated with the beam profile and have determined a considerable background at the small angles.

The background subtraction was carried out by means of a Gauss fit leading to errors up to 15% and 8% for the small and larger angles, respectively.

The typical total errors are up to 18% and 10% for the small and larger angles, respectively.

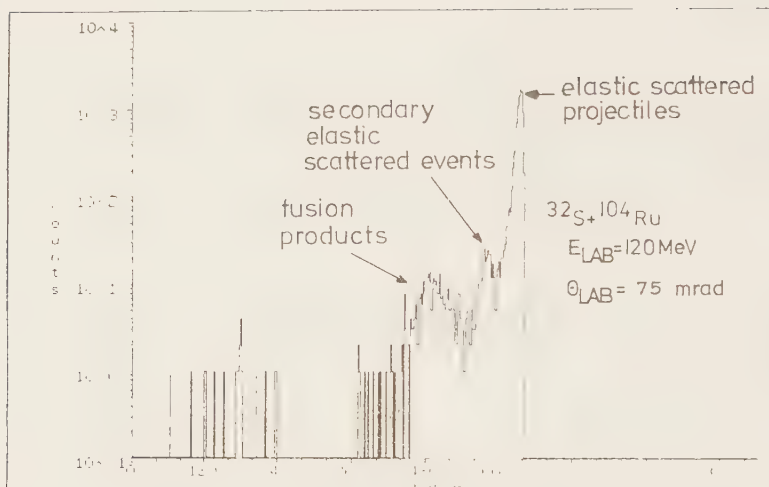


Fig.27: A time-of-flight spectrum showing a secondary elastic scattered peak.

6. RESULTS

For all target-projectile combinations the angular distributions of evaporation residues from near-barrier fusion of $^{32,36}\text{S}$ on $A \sim 100$ nuclei simulated by the Monte Carlo evaporation code TRANMI were fitted to the measured angular distribution resulting in relative intensities of the $(n,n\dots)$, $(p,n\dots)$, $(p,p,n\dots)$ and $(\alpha,n\dots)$ -evaporation events (fig.28).

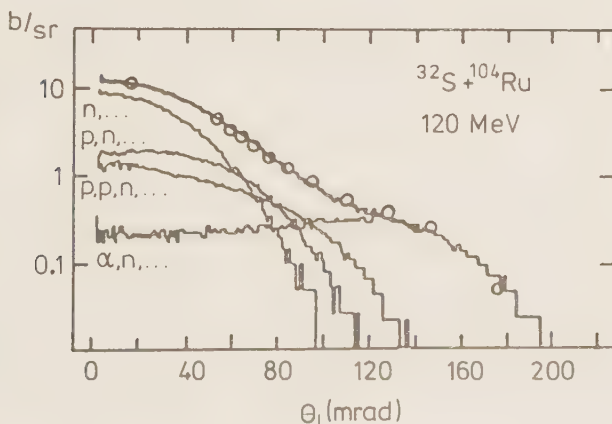


Fig.28: Differential cross section of fusion products. Thin lines: Monte Carlo distributions. Circles: experimental cross sections, thick line: Fit, resulting in relative intensities.

The energy evaporation spectra for neutrons was assumed to be of the form

$$n(E) \sim E e^{-E/T} \quad 120$$

where T is the temperature of the nucleus after a particle

evaporation and is given by $E^* = a T^2$ and $a = A/8$, where A is the mass number and E^* the excitation energy.

A first attempt to obtain the fits was carried out assuming an isotropic angular distribution of the evaporated particles in CM-system and employing the empirical Coulomb barriers of Alexander et al.⁵⁴ for protons and alpha-particles as input for calculating their evaporation spectra, which are shifted upwards in energy by the corresponding Coulomb barriers. A typical Coulomb barrier for protons and alpha-particles was about 8 and 15 MeV, respectively.

No good fits, however, could be achieved in this work in the angular range 80-140 mrad, indicating an anisotropic CM-angular distribution as described in sec.3. It was assumed to be of the weak-coupling type, proposed by Ericson and Strutinsky²¹, having the form $1 + A_2 \cos^2 \theta$. The quantity A_2 was used as additional fit parameter.

A typical anisotropy factor A_2 , for the alpha-evaporation, resulting from the best fit was about 0.40. The detailed results for the various target-projectile combinations are presented and discussed in sec.7.4. Regarding mass dependence, according to the weak-coupling approximation, the anisotropy factor A_2 for neutrons and protons were assumed to be one fourth of that for alpha-particles.

In fig.29 is shown a fit to the measured angular distribution assuming an isotropic evaporation ($A_2=0$) in CM-system and a best fit ($A_2 = 0.40$), suggesting, therefore, a considerable anisotropy.

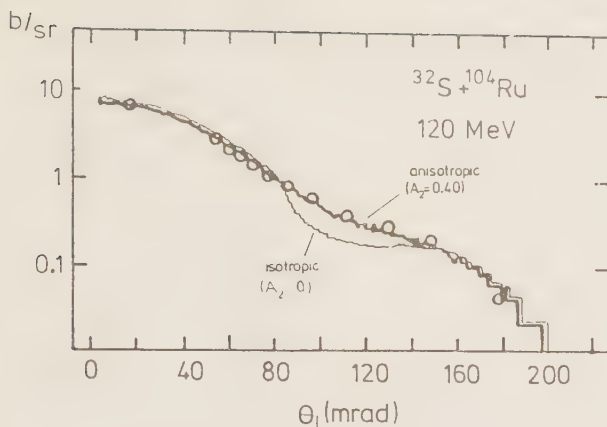


Fig.29: Differential cross section of fusion products. Thin line: Fit assuming isotropic evaporation in CM-system ($A_2 = 0$). Thick line: Fit with anisotropy factor $A_2 = 0.40$.

For these fits the iterative method mentioned in sec.5.4 was employed up to 4 iterations.

The relative intensities of the evaporation events as obtained from the fits are presented in tables 4-5 and are compared to those calculated with the computer code CASCADE, which is described in sec.7.2.

It must be noted that the sum over all calculated relative intensities of the evaporation channels presented in these tables is smaller than 100%, since other channels like ($\alpha, p, n, \dots$) and ($p, p, p, n, \dots$) are present in the calculations. The experimental relative intensities are normalized to 100%.

^{32}S Target	E_{lab} (MeV)											
	120						114					
	Q_n exp	Q_n casc	Q_P exp	Q_P casc	Q_{2P} exp	Q_{2P} casc	Q_n exp	Q_n casc	Q_P exp	Q_P casc	Q_{2P} exp	Q_{2P} casc
^{106}Ru	41.0 $\pm$ 5.6	28.3	22.2 $\pm$ 2.8	46.3	17.6 $\pm$ 2.6	11.3	19.2 $\pm$ 2.0	12.6	44.8 $\pm$ 8.9	31.2	23.0 $\pm$ 4.8	50.1
^{102}Ru	28.5 $\pm$ 4.5	12.4	50.3 $\pm$ 8.0	48.1	10.8 $\pm$ 1.2	27.2	10.4 $\pm$ 1.0	7.0			16.0 $\pm$ 2.0	7.4
^{107}Ru	10.0 $\pm$ 1.6	4.1	49.2 $\pm$ 8.6	38.5	35.5 $\pm$ 6.2	47.3	5.3 $\pm$ 0.6	4.3				
^{108}Ru	8.0 $\pm$ 1.2	2.2	35.8 $\pm$ 6.1	34.2	42.0 $\pm$ 5.4	53.3	14.2 $\pm$ 1.8	2.7	12.2 $\pm$ 1.6	11.4	50.1 $\pm$ 9.8	46.9
^{100}Mo	84.8 $\pm$ 14.4	79.5	2.5 $\pm$ 0.4	12.9	1.2 $\pm$ 0.8	0.1					33.7 $\pm$ 4.2	29.8
^{98}Mo	36.6 $\pm$ 6.0	32.1	50.2 $\pm$ 10.8	44.4	5.2 $\pm$ 0.8	9.5	11.5 $\pm$ 2.1	15.9				
^{96}Mo	23.4 $\pm$ 3.2	12.4	36.8 $\pm$ 7.8	29.0	25.2 $\pm$ 2.8	47.6	14.6 $\pm$ 1.6	6.1	38.0 $\pm$ 7.2	36.1	48.8 $\pm$ 12.1	41.0
^{94}Mo	14.4 $\pm$ 2.3	4.2	42.6 $\pm$ 8.0	26.4	38.6 $\pm$ 5.1	56.3	5.4 $\pm$ 0.6	1.8	6.9 $\pm$ 0.9	12.1		
^{110}Pd	68.0 $\pm$ 10.1	37.6	11.2 $\pm$ 2.0	40.8	8.8 $\pm$ 1.4	4.0						
^{108}Pd	45.1 $\pm$ 8.1	17.2	26.2 $\pm$ 4.8	47.3	13.9 $\pm$ 1.8	15.5	12.0 $\pm$ 1.4	12.1				
^{106}Pd	24.1 $\pm$ 3.9	8.2	49.4 $\pm$ 6.2	42.0	16.7 $\pm$ 2.0	39.8	14.8 $\pm$ 1.6	10.7				
^{105}Pd	14.5 $\pm$ 2.0	4.0	46.0 $\pm$ 9.1	34.4	27.1 $\pm$ 3.2	48.9	12.4 $\pm$ 1.4	3.5	16.5 $\pm$ 2.2	4.9	45.0 $\pm$ 8.9	38.9
^{104}Pd	14.9 $\pm$ 2.3	1.5	38.0 $\pm$ 5.0	26.8	23.1 $\pm$ 5.9	55.1	14.0 $\pm$ 1.2	2.8	16.0 $\pm$ 3.4	3.8	36.4 $\pm$ 5.0	26.5
^{103}Rh	15.0 $\pm$ 3.0	3.9	66.0 $\pm$ 10.1	37.6	12.2 $\pm$ 1.5	45.9	6.8 $\pm$ 0.9	4.0	16.4 $\pm$ 3.1	2.9	63.6 $\pm$ 9.8	49.5
											14.9 $\pm$ 1.8	32.8
											5.1 $\pm$ 0.6	3.9
^{92}Mo	120						114					
	Q_n exp	Q_n casc	Q_{2P} exp	Q_{2P} casc	Q_{2P} exp	Q_{2P} casc	Q_n exp	Q_n casc	Q_{2P} exp	Q_{2P} casc	Q_{2P} exp	Q_{2P} casc
	6.8 $\pm$ 1.2	1.2	39.3 $\pm$ 6.1	29.3	44.5 $\pm$ 6.0	56.5	9.4 $\pm$ 1.4	4.1	16.3 $\pm$ 3.1	1.1	30.0 $\pm$ 5.8	37.8
											45.9 $\pm$ 6.2	46.9
											8.1 $\pm$ 0.6	4.0

Table 4: Summary of relative intensities obtained from the angular distribution of evaporation residues and from the prediction with the computer code CASCADE for near-barrier fusion of $S^{32} + A=100$ nuclei. The angular distribution for the ^{92}Mo case was fitted with the $(n, n...)$, $(p, p, n...)$, $(p, p, p, n, ...)$ and $(\alpha, p, n...)$ -evaporation events, which agrees to another recent measurement⁵⁵.

³⁶ S Target	E _{lab} (MeV)											
	120						114					
	α _n exp	α _n casc	Q _P exp	Q _P casc	α _{2P} exp	α _{2P} casc	α _n exp	α _n casc	Q _P exp	Q _P casc	α _{2P} exp	α _{2P} casc
¹⁰⁴ Ru	82.5±10.1	76.8	4.0±0.6	15.6	2.7±0.3	1.0	6.8±0.8	5.8	81.4±10.2	79.1	5.3±0.7	16.1
¹⁰² Ru	86.5±12.5	63.0	2.4±0.4	26.0	3.1±0.4	1.1	8.0±0.9	7.8			2.5±0.3	1.0
¹⁰¹ Ru	59.8±11.8	44.0	20.0±3.8	36.8	6.2±0.9	2.9	14.0±1.7	9.5				
¹⁰⁰ Ru	64.5±8.2	39.7	14.1±1.8	41.7	10.8±1.5	4.4	10.6±1.2	9.4				
¹⁰⁰ Mo	75.6±12.1	79.5	14.2±1.6	12.9	3.8±0.5	1.0	6.4±0.8	5.9	82.1±10.4	81.2	15.1±1.5	11.1
⁹⁸ Mo	69.8±11.9	68.7	15.9±2.9	21.3	3.0±0.3	1.0	12.1±1.2	7.8	74.0±9.8	73.5	16.4±3.0	19.6
⁹⁶ Mo	64.8±10.8	41.7	16.9±3.1	43.4	3.9±0.4	2.0	11.2±0.9	9.6			2.8±0.3	1.0
⁹⁴ Mo	36.8±4.6	16.8	35.6±4.4	56.7	12.8±1.3	11.5	14.8±1.5	9.7				
¹¹⁰ Pd	86.0±12.1	186.5	4.1±0.8	7.8	5.8±0.6	0.5	4.3±0.5	3.6				
¹⁰⁸ Pd	81.5±12.0	75.4	4.8±1.1	16.2	3.5±0.5	1.0	10.2±1.2	5.4				
¹⁰⁶ Pd	80.5±15.6	69.5	8.2±1.4	20.4	1.9±0.3	2.1	9.4±0.9	5.4				
¹⁰⁵ Pd	74.8±12.8	41.5	5.1±0.9	40.6	2.9±0.3	6.9	17.2±1.8	8.0				
¹⁰⁴ Pd	42.8±6.8	35.1	25.9±3.2	42.2	14.5±1.6	9.3	16.8±1.4	9.0				
¹⁰³ Rh	52.8±12.4	18.9	34.5±6.2	49.1	3.8±0.4	1.9	8.9±0.9	8.6				
⁹² Mo	36.4±4.1	3.3	23.4±2.5	4.3	31.5±3.2	42.5	8.5±1.0	7.5				

Table 5: Same as table 2, for ³⁶S-projectiles. The angular distributions for the ⁹²Mo case was fitted with the (n,n...), (p,n...), (p,p,n,...) and (α,p,n,...)-evaporation events.

The relative intensities for the alpha-evaporation residues are discussed in sec.7.3

The relative intensities of the evaporation events obtained from the angular distributions were used to evaluate the total detection efficiency of the Munich RF-Recoil Spectrometer according to eq.80. These results are shown in table 6 and 7 and are compared to those originally obtained from the velocity distributions.

ϵ				
Target	$E_{lab} (MeV)$			
	120		114	
	ang.distr.	vel.distr.	ang.distr.	vel.distr.
^{104}Ru	9.8 ± 1.3	11.9 ± 1.2	9.5 ± 1.4	10.8 ± 1.1
^{102}Ru	9.7 ± 1.5	11.6 ± 1.4		
^{101}Ru	7.9 ± 1.3	9.0 ± 1.1	8.6 ± 1.6	9.2 ± 1.2
^{100}Ru	7.5 ± 1.2	8.6 ± 1.2		
^{100}Mo	13.6 ± 2.2	16.6 ± 1.8		
^{98}Mo	10.4 ± 1.9	12.2 ± 1.4	12.1 ± 1.4	11.6 ± 0.8
^{96}Mo	9.6 ± 1.4	11.1 ± 1.1		
^{94}Mo	9.5 ± 1.5	11.1 ± 0.9		
^{92}Mo	6.4 ± 0.8	5.3 ± 0.5		
^{110}Pd	13.1 ± 2.1	17.7 ± 1.6		
^{108}Pd	10.7 ± 2.0	13.9 ± 2.0		
^{106}Pd	9.9 ± 1.4	11.9 ± 1.2		
^{105}Pd	8.6 ± 1.3	10.6 ± 1.0	9.8 ± 1.4	10.9 ± 1.0
^{104}Pd	9.5 ± 1.4	10.8 ± 1.1	9.6 ± 1.2	10.5 ± 1.0
^{103}Rh	9.2 ± 1.2	9.4 ± 0.8	9.2 ± 1.4	9.4 ± 0.9

Table 6: Summary of measured total detection efficiency with ^{32}S beams for the recoil spectrometer. The angular distribution and the velocity distribution methods were carried out by means of the ring detector and recoil spectrometer, which are described in secs.5.3 and 5.2, respectively.

Target	ε			
	$E_{\text{lab}} \text{ (MeV)}$			
	120		114	
	ang. distr.	vel. distr.	ang. distr.	vel. distr.
^{104}Ru	17.4 ± 2.1	20.4 ± 1.6	18.4 ± 2.2	22.2 ± 1.7
^{102}Ru	20.1 ± 2.9	22.7 ± 1.8		
^{101}Ru	16.1 ± 3.1	19.0 ± 2.6		
^{100}Ru	17.1 ± 2.2	20.3 ± 1.3		
^{100}Mo	21.3 ± 2.6	18.3 ± 2.6	20.9 ± 2.1	18.8 ± 2.7
^{98}Mo	16.3 ± 2.7	18.6 ± 1.0	17.4 ± 2.6	19.6 ± 1.4
^{96}Mo	16.2 ± 2.6	18.0 ± 1.4		
^{94}Mo	13.5 ± 1.6	15.0 ± 1.4		
^{92}Mo	7.9 ± 0.8	9.6 ± 2.8		
^{110}Pd	19.5 ± 2.7	21.7 ± 2.1		
^{108}Pd	19.6 ± 2.9	23.1 ± 1.9		
^{106}Pd	21.4 ± 3.1	24.0 ± 1.5		
^{105}Pd	19.8 ± 3.4	22.5 ± 1.9		
^{104}Pd	15.9 ± 2.4	16.1 ± 3.9		
^{103}Rh	16.5 ± 2.8	16.0 ± 1.9		

Table 7: Same as table 6, for ^{36}S -projectiles.

7. DISCUSSION OF RESULTS

7.1 THE HAUSER-FESHBACH THEORY

The Hauser-Feshbach⁵⁶ theory removes the shortcoming of the Weisskopf-theory⁵⁷ which does not account for angular momentum and parity conservation in order to calculate the angle-integrated cross section for a decay channel.

The angle-integrated cross section $\bar{\sigma}_{\alpha\alpha'}$ for a decay channel α' from an entrance channel α , can be determined by a set of quantum numbers

$$C_{T,i} = \{ \alpha, \alpha', s, s', l, l', J \} \quad 120$$

for the initial and final states, where

α and α' are the entrance and a particular exit channel.

i and I are the ground-state spins of projectile and target, respectively.

s or s' are entrance and exit channel spins.

l and l' are the orbital angular momenta.

J is the total angular momentum of the compound nucleus.

If we apply the arguments of section 2 (eq.2) the cross section $\bar{\sigma}_{\alpha\alpha'}$ can be factorized into the compound nucleus formation in channel α and the branching probability into

of the decay channel α'

$$\Gamma_{\alpha\alpha'} = \frac{4\pi}{k_\alpha^2} \sum_{J\pi} \frac{2J+1}{(2I+1)(2i+1)} \frac{\left(\sum_{\ell,s} T_\ell(\alpha) \right)_{J\pi} \cdot \left(\sum_{\ell',s'} T_{\ell'}(\alpha') \right)_{J\pi}}{N(J\pi)} \quad 121$$

where

$$N(J\pi) = \left(\sum_{\ell'', s'', \alpha''} T_{\ell''}(\alpha'') \right)_{J\pi} \quad 122$$

The double dashed indices refer to any two-body exit channel and

k_α is the wave number of the entrance channel

T_ℓ is the transmission coefficient .

The following angular momentum algebra has to be taken into account

$$\vec{\ell} + \vec{s} = \vec{J} = \vec{\ell}' + \vec{s}' = \vec{\ell}'' + \vec{s}'' \quad , \quad \vec{\ell} = \vec{l} + \vec{I} \quad 123$$

The partial width $\Gamma_\ell(\alpha)$ for decay of the compound nucleus with excitation energy E and angular momentum J into a channel α is related to the transmission coefficient $T_\ell(\alpha)$ by

$$\Gamma_\ell(\alpha) = \frac{T_\ell(\alpha)}{2\pi \rho(E, J)} \quad 124$$

where $\rho(E, J)$ is the spin dependent level density of the compound nucleus.

According to R.M.Shaw et al.⁵⁸ the level density can be calculated for high excitation energies within the Fermi-gas model, according to the formula

$$\rho(U, J) = \frac{2J+1}{12 \bar{a}^{1/4} (U+T)^{5/4} (2\sigma^2)^{3/2}} \exp\left[2\sqrt{\bar{a}U} - \frac{(J+1/2)^2}{2\sigma^2}\right]$$

$$E^* = U + \Delta, \quad U = \dots, \quad \sigma^2 = \dots / \hbar^2$$

where

Δ is the pairing energy

$\bar{a}$ is the level density parameter

σ^2 is the moment of inertia

σ is the spin cut-off parameter

T is the nuclear temperature

The moment of inertia of a rigid body is given by

$$J_{\text{rigid}} = \frac{2}{5} m A^{5/3} r_0^2$$

The Hauser Feshbach-formalism is employed in the computer code CASCADE to determine mass- and charge distributions of residual nuclei. The parameters used to the corresponding numerical calculations are discussed below.

7.2 CASCADE PROGRAM

The computer code CASCADE⁵⁹ employs the Hauser Feshbach theory to determine mass- and charge distributions for the decay channels in a compound nucleus process. It predicts the relative intensities (decay widths) for fission, particle and gamma emission.

For the particle decay modes, the code considers basically neutron, proton and alpha particle evaporations. Evaporation of deuterons becomes important at higher excitation energies (when the nuclear temperature is greater than 3 MeV). Evaporation of ${}^6\text{Li}$ may be significant in a light nucleus at angular momenta close to the yrast line. However, in the preset application, these channels were not relevant.

In order to get the relative intensities for all possible channels, the transmission coefficients for the evaporated particles are obtained using the Hauser Feshbach formula and the decay probabilities are obtained from level densities in the daughter nucleus.

The fission partial width is determined by the total number of available states at the saddle point, taking into account angular momentum and energy conservation. In the present cases, fission can be neglected.

The gamma-decay is treated statistically, i.e. with average reduced strength valid for all transitions.

In the present near-barrier fusion measurement the compound nuclei have a typical initial excitation energy of about 50 MeV. For such an energy the code assumes that all compound nuclei behave as predicted by the liquid-drop model and the level densities are obtained from the Fermi gas

formula.

The pairing energy Δ is calculated as $\pm 11/A^{1/2}$ MeV for odd or even nuclei and zero for odd-mass nuclei⁶⁰.

The transmission coefficients for the evaporated particles were calculated from the optical model. The radius parameter, potential depth and diffuseness for neutrons are given by Wilmore and Hodgson⁶¹, for protons those of Perey⁶² and for alpha-particles those of Huizenga and Igo⁶³.

The parameters used for the gamma decay are listed in table 8.

γ -decay widths (in Weisskopf units)	
$\xi E1$	10^{-4}
$\xi M1$	$3 \cdot 10^{-2}$
$\xi E2$	5

Table 8: Parameters employed to calculate the gamma decay in the fusion of $^{32,36}\text{S}$ -ions with $^{92,94,96,98,100}\text{Mo}$, $^{100,101,102,104}\text{Ru}$, ^{103}Rh and $^{104,105,106,108,110}\text{Pd}$.

The level density parameter is calculated by $a=A/DA$, where $DA \sim 8$ MeV.

Average rms radii derived from electron scattering data are used, as cited by Myers⁶⁴.

7.3 ENERGY DEPENDENCE FOR THE ALPHA-EVAPORATION CHANNEL

One important aim of this study is to determine the influence of the alpha-evaporation residues on the total efficiency of the Munich RF-recoil spectrometer.

A comparison between the measured relative intensity of the alpha-evaporation residues with those calculated within the computer code CASCADE were carried out in order to estimate the intensity of this channel on the energy range spanned by the near-coulomb fusion measurements.

The calculations with the Cascade program were extended as far below the barrier until the measured cross section were around 100 micro-barn²⁰ and normalized at $E_{lab} = 120$ MeV. These results are shown in figs.30-31.

It is important to note that the predicted trends for the alpha intensity channel agrees with those determined within the present measurement. Therefore the agreement of the total detection efficiency for the recoil spectrometer by means of angular distributions and velocity distributions (Tables 6-7) gives an evidence that the last method, even resulting in a larger error of the alpha-residues intensity, is still suited for energies up to 12 MeV below the Coulomb barrier.

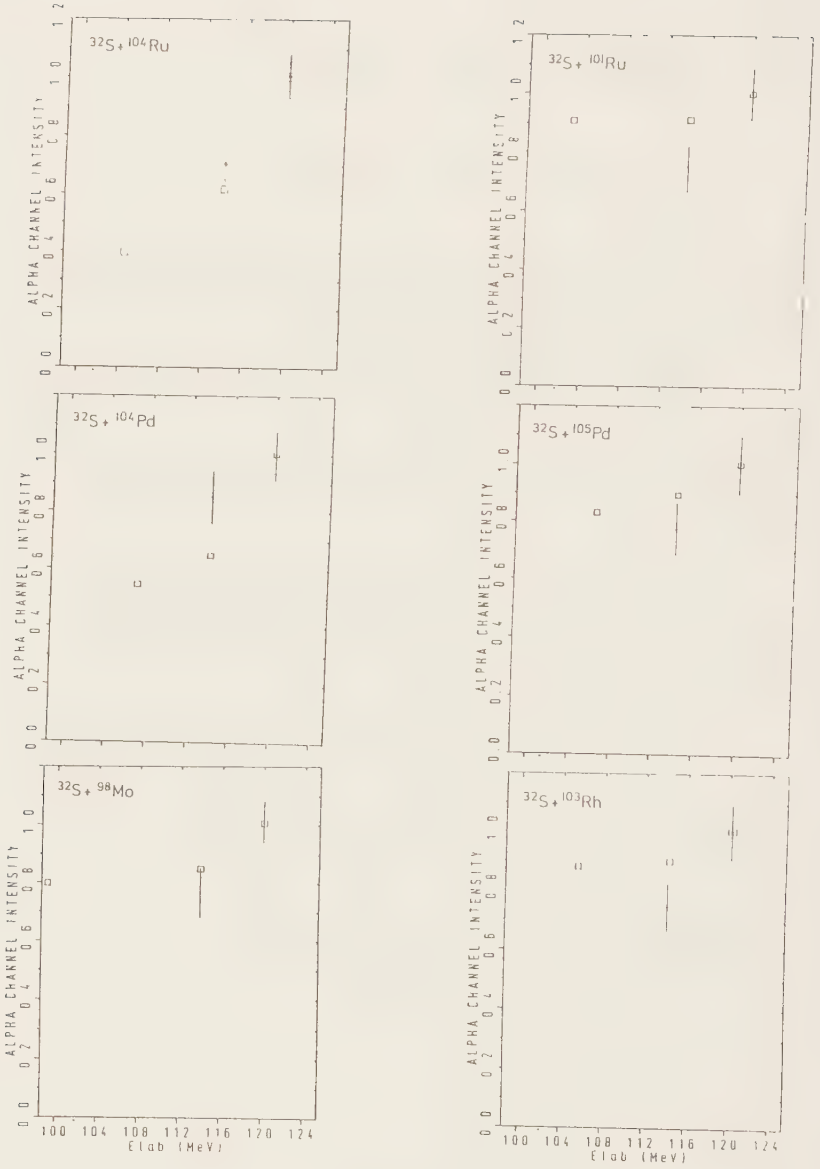


Fig.30: Alpha intensity channel normalized at $E_{lab} = 120$ MeV for the near-barrier fusion of $^{36}\text{S} + ^{104}\text{Ru}$ and $^{100,98}\text{Mo}$. Full circles:measured normalized alpha-intensities. Squares:predicted normalized alpha-intensities.

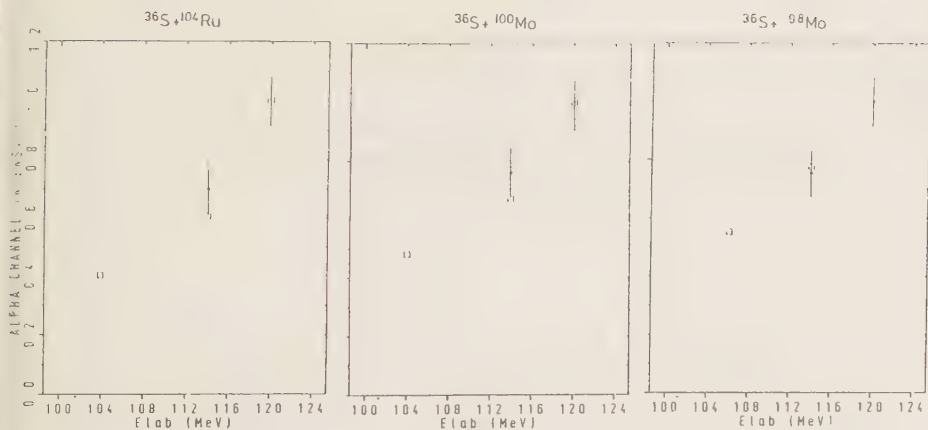


Fig.31: Alpha intensity channel normalized at $E_{lab} = 120$ MeV for the near-barrier fusion of $^{32}\text{S} + ^{104,101}\text{Ru}$, ^{98}Mo , $^{105,104}\text{Pd}$ and ^{103}Rh . Full circles:measured normalized alpha-intensities. Squares:predicted normalized alpha-intensities.

7.4 INTERPRETATION OF THE ANISOTROPY ENHANCEMENT FOR AN ALPHA-PARTICLE EVAPORATION

In a compound nucleus reaction process, after the target nucleus has captured the projectile, the system rotates about an axis perpendicular to the incident beam in order to conserve the asymptotic angular momentum. This restriction is the physical reason for the anisotropy of the evaporated particles as discussed in section 2.

In the case of weak-coupling⁽²¹⁾ the anisotropy for the evaporation of a particle of energy E_2 in the direction $\hat{n}$ with angular momentum $\vec{l}(E_2)$ from a compound nucleus with angular momentum $\vec{L}$ (see Fig.32) is in first order

$$W(\hat{n}, E_2) \propto 1 + \frac{\alpha_f^2 \langle L^2 \rangle \langle l^2(E_2) \rangle}{2} \cos^2 \Theta \quad 128$$

where

α_f is related to the moment of inertia and nuclear temperature of the final nucleus by $\hbar^2/2\mathcal{I}T$ (see eq.10).

$\langle L^2 \rangle$ and $\langle l^2(E_2) \rangle$ are averages of L and $l(E_2)$, with the relative weighting factors $L T_1(L)$ and $l(E_2) T_2(l(E_2))$, respectively. The quantity T_1 is the transmission coefficient for the compound nucleus formation and T_2 is the transmission coefficient for a subsequent particle evaporation.

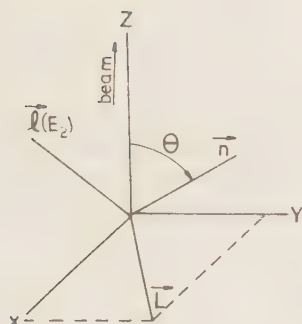


Fig.32: Definition of angle θ for a particle with angular momentum $\vec{l}(E_2)$ which is evaporated from a compound nucleus with angular momentum $\vec{L}$. $\vec{L}$ lies in the xy -plane.

If the average of the angular momentum of the compound nucleus is performed using the sharp cut-off approximation it is possible to write

$$\langle L^2 \rangle = \mu_1 \frac{E_1 - B_1}{\hbar^2} R_1^2 \quad 129$$

where

E_1 is the energy of the projectile.

μ_1 is the reduced mass.

B_1 is the Coulomb barrier.

R_1 is the interaction radius.

Similarly, for the outgoing particle with energy E_2 the average angular momentum can be obtained by

$$\langle l^2(E_2) \rangle = \frac{1}{2} \frac{l^2(E_2)}{\mu_2} = \mu_2 \frac{E_2 - B_2}{\hbar^2} R_2^2 \quad 130$$

Averaging $\langle l^2(E_2) \rangle$ over the following energy distribution (for evaporated neutrons)

$$H(E_2) dE_2 = \text{const.} \sqrt{E_2} e^{-E_2/T} dE_2 \quad 131$$

results in (for $B_2 = 0$)

$$\langle l^2 \rangle = \frac{3}{2} \mu_2 \frac{T}{\hbar^2} R_2^2 \quad 132$$

where T is the nuclear temperature.

If, for charged particles, the energy distribution is, in good approximation, assumed to be

$$H(E_2) dE_2 = \text{const.} \sqrt{E_2 - B_2} e^{-(E_2 - B_2)/T} dE_2 \quad 133$$

the same eq.132 results for $\langle l^2 \rangle$ in the case of protons and alpha-particles.

Besides eq.129 the average $\langle L^2 \rangle$ can be expressed as

$$\langle L^2 \rangle = \frac{J^2 \langle \omega^2 \rangle}{\hbar^2} \quad 134$$

where J and ω are the moment of inertia and the angular velocity of the compound nucleus, respectively.

Expressing the eq.128 in the form

$$W(\vec{n}) = 1 + A_2 \cos^2 \theta \quad 135$$

and combining the eqs.132,134 with eq.135 the anisotropy factor A_2 can be written approximately as

$$A_2 \approx \frac{3}{4} \mu_2 \frac{\omega^2}{4\pi} R_2^2 \quad 136$$

In this classical picture the anisotropy depends on the ratio of the centrifugal energy of an evaporated particle due to the compound nucleus rotation, and its average kinetic energy at the nuclear surface.

According to eq.136 the anisotropy for an alpha-particle evaporation event must be 4 times larger than those for neutrons or protons due to mass differences. The more massive particle can carry off more angular momentum for a given energy, therefore the alpha-evaporation events are well suited to investigate anisotropy effects.

According to eq.128 the anisotropy factor A_2 is proportional to $\langle L^2 \rangle$ and $\langle l^2 \rangle$, consequently it contains information about the angular momentum distributions of the compound nucleus formation and evaporation processes.

Employing the barrier fluctuation formalism an angular momentum distribution for the compound nucleus formation can be determined according to eq.61 using the standard deviations σ_{fit} that reproduce the near-barrier excitation function for the systems considered in this work⁶⁵. Similarly an angular momentum distribution predicted by the one-dimensional tunneling can be determined assuming a standard deviation equal to zero as is shown in fig.33.

From these two kinds of angular momentum distribution the average angular momenta ($\langle L^2 \rangle_{\text{fit}}$, $\langle L^2 \rangle_{\text{fit} = 0}$) have been extracted at an incident laboratory energy of 120 MeV. Under the assumption that the formation and decay of a compound nucleus can be described as independent events and that the coupling effects which enhance the sub-barrier fusion cross sections have negligible influence on the λ -distribution, the ratio

$$(\langle L^2 \rangle_{\text{fit}}) / (\langle L^2 \rangle_{\text{fit} = 0})$$

represents the anisotropy enhancement with respect to the one-dimensional tunneling calculation, as obtained from the experimental excitation functions (contained in $\bar{\sigma}_{fit}$) of sub-coulomb fusion. These ratios were compared with that obtained from the experimental anisotropy A_2^{EXP} (at $E_{lab} = 120$ MeV, obtained from the measured angular distributions) and the one derived from the statistical model within the computer code Cascade A_2^{CAS} (evaluating the eq.128, see also eq.14) as is shown in Tables 9-10.

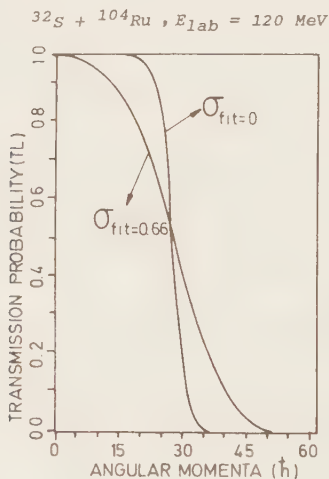


Fig.33: Typical angular momentum distribution according to the barrier fluctuation formalism in order to reproduce the measured fusion cross section ($\bar{\sigma}_{fit} = 0.66$) and predicted by one-dimensional tunneling ($\bar{\sigma}_{fit} = 0$). For all projectile-target combinations the Coulomb barriers were determined employing the proximity potential $V_n(r-s-R_1-R_2-\Delta R)$ with a fixed barrier correction $\Delta R = 0.25$ fm. The quantity s represents the fluctuation of the surface-to-surface distance equivalent to a corresponding barrier fluctuation (see eq.61).

The experimental anisotropy enhancement are in relative accordance with the ones obtained from the excitation functions. A difficulty in extracting the anisotropy factor from the measured angular distribution as a fit parameter lies in the fact that its experimental error depends essentially on relative alpha-residue intensity. For the experimental anisotropy factor A_2^{exp} errors larger than 30% are determined when the alpha-residue relative intensities are smaller than 10%.

$\begin{smallmatrix} ^{32}\text{S} \\ \text{Target} \end{smallmatrix}$	σ_{fit}	$\frac{\langle L^2 \rangle \sigma_{\text{fit}}}{\langle L^2 \rangle \sigma_{\text{fit}=0}^{\text{exp}}}$	A_2^{exp}	$\frac{A_2^{\text{exp}}}{A_2^{\text{asc}}}$
^{104}Ru	0.66	1.49 ± 0.16	0.40 ± 0.06	1.74 ± 0.26
^{102}Ru	0.60	1.73 ± 0.21	0.41 ± 0.08	1.66 ± 0.29
^{100}Ru	0.55	1.66 ± 0.17	0.38 ± 0.06	1.67 ± 0.23
^{100}Mo	0.62	1.26 ± 0.16	0.37 ± 0.08	1.48 ± 0.24
^{110}Pd	0.54	1.56 ± 0.19	0.42 ± 0.08	1.68 ± 0.32
^{108}Pd	0.60	1.59 ± 0.20	0.41 ± 0.06	1.58 ± 0.23
^{106}Pd	0.48	1.66 ± 0.22	0.43 ± 0.09	1.72 ± 0.36
^{105}Pd	0.50	1.83 ± 0.24	0.43 ± 0.08	1.84 ± 0.39
^{104}Pd	0.49	1.91 ± 0.26	0.42 ± 0.06	1.85 ± 0.21

Table 9: Summary of experimental anisotropy enhancements for the near-barrier fusion of $^{32}\text{S} + \text{A-nuclei}$. The typical experimental errors associated with σ_{fit} are about 5%. Additional uncertainties due to the barrier radius and barrier height are not contained in column 3.

^{36}S Target	σ_{fit}	$\frac{\langle L^2 \rangle_{\sigma_{\text{fit}}}}{\langle L^2 \rangle_{\sigma_{\text{fit}}=0}}$	A_2^{exp}	$\frac{A_2^{\text{exp}}}{A_2^{\text{asc}}}$
^{101}Ru	0.51	1.84 ± 0.21	0.39 ± 0.06	1.56 ± 0.24
^{100}Ru	0.49	1.89 ± 0.22	0.41 ± 0.07	1.64 ± 0.28
^{96}Mo	0.47	1.32 ± 0.17	0.38 ± 0.06	1.46 ± 0.25
^{94}Mo	0.50	1.50 ± 0.18	0.42 ± 0.06	1.76 ± 0.25
^{108}Pd	0.50	2.10 ± 0.22	0.43 ± 0.09	1.58 ± 0.31
^{105}Pd	0.50	2.20 ± 0.24	0.41 ± 0.06	1.66 ± 0.21
^{104}Pd	0.49	2.10 ± 0.25	0.41 ± 0.06	1.58 ± 0.23

Table 10: Same as table 9, for ^{36}S projectiles.

The relative $\langle L^2 \rangle$ depend strongly on the energy difference $E_{\text{cm}} - V_B$ (see fig.34, below). Since both tables refer to $E_{\text{lab}} = 120$ MeV, the smaller σ_{fit} for ^{36}S are over-compensated by the smaller cm-energies, which leads to larger $[\langle L^2 \rangle \sigma_{\text{fit}} / \langle L^2 \rangle \sigma_{\text{fit}} = 0]$. Also the large variations of the ratio within one table are mainly due to this effect.

The strong enhancement of the sub-barrier fusion cross sections has been, as mentioned before, described very successfully by the coupled channel mechanism. In this picture also the anisotropy enhancement, which has the same physical basis as the fusion enhancement, can be discussed regarding that the angular momentum distributions of the compound nucleus are significantly altered by the coupled channels effects⁶⁶⁻⁷².

The L-distribution dependence of the anisotropy factor A_2 is sensitive to effects of the coupling interactions on the distribution of fusion cross sections per partial wave

as compared to conventional potential models without such a coupling.

These effects can be illustrated in fig.34 which shows that maximum effect of the coupling on the average compound nuclear angular momentum L is found at bombarding energy close to the Coulomb barrier.

The curves $\langle L(E) \rangle$ of fig.34 have been obtained by the following estimates. The near-barrier compound nucleus angular momentum distribution can be characterized within three energy ranges related to the barrier height V_B and the total coupling strength F .

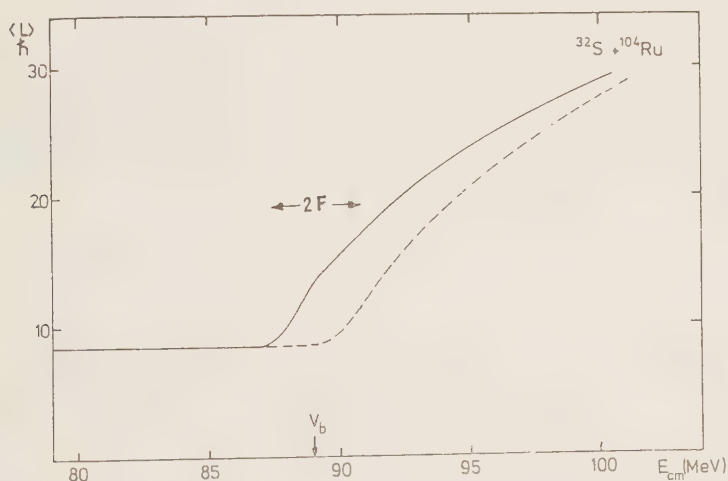


Fig.34: Average angular momentum for the $^{32}\text{S} + ^{104}\text{Ru}$ fusion reaction versus bombarding energy calculated with (solid) and without (dashed) the coupling interactions used to describe the fusion cross sections in ref.(20) (cf. S.Landowne⁷³)

For higher energy range where $E > V_B + F$ the angular momentum distribution, in the absence of coupling

interactions, approaches a triangular form and the average angular momentum is approximately given by the classical limit

$$\langle L \rangle \simeq \frac{2}{3} \sqrt{2\mu r_B^2 (E - V_B) / \hbar^2} \quad 138$$

where μ is the reduced mass

r_B is the barrier radial position

In the presence of coupling interactions, also in the energy range $E > V_B + F$, the average angular momentum is approximately given by⁷³

$$\langle L \rangle \simeq \frac{2}{3} \sqrt{2\mu r_B^2 [E - (V_B - F)] / \hbar^2} \quad 139$$

For the lower energy range, where $E < V_B - F$ the angular momentum distribution in the presence or absence of coupling interactions is independent of the bombarding energy (see example fig.15, p.33) and is (assuming a parabolic barrier) given by

$$\rho(L) \sim (2L+1) T_L = (2L+1) e^{-L(L+1)/a^2} \quad 140$$

where

$$a^2 \equiv 2\mu r_B^2 \mathcal{E} / \hbar^2 \quad 141$$

and $\mathcal{E}$ is the barrier thickness. The average angular momentum becomes independent of energy. It can be calculated easily replacing $L(L+1)$ by L^2 and the summation by an integration over L to be

$$\langle L \rangle = \frac{\sqrt{\pi}}{2} a \simeq \frac{2}{3} \sqrt{2\mu r_B^2 (2\mathcal{E}) / \hbar^2} \quad 142$$

In the absence of coupling interactions eq.140 is still

valid up to $E = V_B$ and for $V_B < E < V_B + F$ the curve $\langle L(E) \rangle$ is assumed to be interpolated within the eqs.138, 142.

In the presence of coupling interactions the intermediate energy range of the curve $\langle L(E) \rangle$ is assumed to be interpolated between the two limiting situations⁷³, giving rise to a rough estimate for the average angular momentum for $E \sim V_B$

$$\langle L \rangle \simeq \frac{2}{3} \sqrt{2\mu r_B^2 F / \hbar^2} \quad 143$$

Assuming again that the λ -distribution is unaffected by barrier fluctuation effects, the anisotropy enhancement with respect to the nocoupling limit can be obtained by the ratio $[\langle L^2 \rangle_{\text{coupl.}} / \langle L^2 \rangle_{\text{nocoupl.}}]$ (the numerator and denominator are the average squared angular momentum with and without coupling interactions, respectively, see fig.34). For the systems investigated in this work the following relation

$$[\langle L^2 \rangle_{\text{coupl.}} / \langle L^2 \rangle_{\text{nocoupl.}}] \sim [\langle L \rangle_{\text{coupl.}}^2 / \langle L \rangle_{\text{nocoupl.}}^2] \quad 144$$

is quite well suited (within a few per cent), that is, the relation between the averages $\langle L^2 \rangle$ and $\langle L \rangle^2$ can be assumed unaffected by the presence of coupling interactions.

Combining the eqs.142-144 results finally in

$$[\langle L^2 \rangle_{\text{coupl.}} / \langle L^2 \rangle_{\text{nocoupl.}}] \sim F/2\epsilon \quad 145$$

and thus for the coupled channels estimate of the anisotropy enhancement

$$[A_2^{\text{coupl.}} / A_2^{\text{nocoupl.}}] \sim F/2\epsilon. \quad 146$$

A detailed analysis of the fusion excitation functions of $^{32,36}\text{S}$ on $A \sim 100$ nuclei²⁰ on the basis of the constant coupling channels framework was carried out⁷⁴. For $^{32,36}\text{S}$ -projectiles the inelastic excitation of the first 2^+ states of both target and projectile and the first 3^- state of the target were taken into account. A typical average coupling strength calculated from the inelastic form factor at the barrier

$$F = \frac{\beta_\lambda R}{\sqrt{4\pi}} \frac{Z_1 Z_2}{r_B^2} e^2 \left\{ 1 - \frac{3}{2\lambda+1} \left(\frac{R}{r_B} \right)^{\lambda-1} \right\} \quad 147$$

turned out to be about $\langle F \rangle \sim 1.0 - 2.5$ Mev (here $\beta_\lambda R$ is the deformation length related to the transition probabilities $B(E\lambda)$ and $R = 1.2 A^{1/3}$). The typical barrier thickness is about $\xi = 0.60$ MeV. For ^{36}S -projectiles (with negative Q neutron transfer channels) one gets

$$F/2\xi \sim 0.9 - 2.2 \quad 148$$

For ^{32}S -projectiles, in addition to the inelastic channels, the $2n$ -transfer channels with positive Q -value have to be taken into account. This was done representing transfer to the ground state and the excited state by an effective transfer to the ground state only. It turned out that an effective transfer strength of $F \sim 1.8$ MeV reproduced the excitation functions in this case, resulting in a somewhat larger but not very different $F/2\xi$ -ratio as in the case of ^{36}S .

The -admittedly- very rough coupled channel estimate of the near-barrier anisotropy enhancement should be compared with the experimental anisotropy enhancement (also determined near the Coulomb barrier) of

$$\left\langle \frac{A_{\text{exp}}}{A_{\text{theor}}} \right\rangle \sim 1.5 - 1.8$$

1-11

(tables 9 and 10, last column) and with the relative increase of the average squared angular momentum of the fused system as derived from the excitation functions (tables 9 and 10, center column). All these ratios are in satisfactory agreement. The agreement of the latter two (the two experimental ratios) is of particular value. A reduction of the experimental uncertainties and a more realistic theoretical estimate are, of course, desirable. The agreement supports, however, the picture of a fluctuating barrier as causing the fusion enhancement and, -at the same time-, the modification of the angular momentum distribution. They also support the theoretical interpretation of the fluctuation as being caused by coupled channels effects.

8. CONCLUSIONS

Concerning the total efficiency of the recoil spectrometer for the near-barrier fusion of $^{32,36}\text{S}$ ions with $^{92,94,96,98,100}\text{Mo}$, $^{100,101,102,104}\text{Ru}$, ^{103}Rh , and $^{104,105,106,108,110}\text{Pd}$ the recoil angular distributions lead to similar results as those originally derived with the recoil velocity distributions. This fact confirms that the recoil velocity is also suited to determine the total efficiency of the recoil spectrometer at energies far below (~ 12 MeV) the barrier, where the alpha intensities are smaller (giving rise to smaller errors).

The magnitude of the anisotropy enhancement obtained from the angular distributions may be decreased by decreasing the nuclear moment of inertia below the rigid body value or demanding a steeper dependence of the level density on excitation energy (both resulting in a lower nuclear temperature for a given excitation energy). If the nuclear moment of inertia is decreased substantially below the rigid body value (40%) the anisotropy enhancement vanishes. Such a large decrease in the moment of inertia is doubtful on energetic grounds even for compound system of excitation energies of about 15 MeV⁵⁹. On the other hand, a steeper dependence of the level density on excitation energy is not appropriate, since for the typical excitation energy 50 MeV of the systems in this work the level density parameter ($A/8$ MeV, employed in the calculations with the computer code CASCADE) seems to be quite suited⁵⁹.

It is worth noting that not only the multiplicity distributions of gamma-rays but also the angular distribution of evaporation residues can be considered as a doorway to obtain more complete information on the angular momentum distribution of fusion reaction near the Coulomb barrier.

In order to obtain a more accurate information on the coupling effects by means of the anisotropy enhancements, their errors could be reduced by i) increasing the number of measured points in the angular distributions, ii) reducing the background (which gives rise to large experimental errors) in the time-of-flight spectra.

A system whose excitation function for sub-barrier fusion can be only reproduced by a large coupling strength ($^{40}\text{Ar} + ^{122}\text{Sn}$, $E = 4\text{--}5\text{ MeV}$)⁷³ would be a very good choice to investigate its angular distribution of evaporation residues, since it must exhibit a very large anisotropy enhancement.

Summary of measured differential fusion cross sections with ^{32}S projectiles at $E_{\text{lab}} = 120$ MeV.

Target	θ_L (mrad)	$\frac{d\sigma(\theta_L)}{d\Omega}$ (mb/sr)	total error (mb/sr)	Target	θ_L (mrad)	$\frac{d\sigma(\theta_L)}{d\Omega}$ (mb/sr)	total error (mb/sr)
^{104}Ru	52	4143	689	^{102}Ru	52	6414	912
	58	3600	441		58	5286	725
	63	3122	399		63	4127	601
	68	2400	310		68	3648	595
	75	1890	261		75	2374	337
	83	1299	149		83	1443	211
	94	972	139		94	849	101
	109	580	57		109	382	43
	127	322	31		127	211	22
	146	246	29		146	161	18
	176	49	8		176	41	7
^{101}Ru	52	6420	991	^{100}Ru	52	5840	967
	58	5220	751		58	4911	791
	63	4620	691		63	4538	769
	68	3850	595		68	3642	599
	75	2850	479		75	3096	441
	83	2088	309		83	2321	301
	94	1420	195		94	1512	189
	109	495	82		109	715	91
	127	182	21		127	353	41
	146	90	10		146	241	26
	176	29	5		176	58	6
^{100}Mo	52	10600	1521	^{98}Mo	52	9801	1491
	58	7543	1017		58	7637	1099
	63	6228	941		63	6523	937
	68	3680	599		68	4968	735
	75	2650	387		75	3379	460
	83	1267	153		83	2136	312
	94	1001	121		94	1068	129
	109	579	69		109	521	61
	127	453	49		127	89	34
	146	328	35		146	194	22
	176	127	12		176	68	8

Target	θ_L (mrad)	$\frac{d\sigma(\theta_L)}{d\Omega}$ (mb/sr)	total error (mb/sr)	Target	θ_L (mrad)	$\frac{d\sigma(\theta_L)}{d\Omega}$ (mb/sr)	total error (mb/sr)
^{96}Mo	52	11426	1791	^{94}Mo	52	1124	1640
	58	9740	1543		58	9674	1492
	63	8100	1240		63	8673	1199
	68	6687	1002		68	7423	1051
	75	8448	1291		75	5445	902
	83	5332	651		83	4289	514
	94	2230	305		94	2329	290
	109	1082	128		109	758	88
	127	596	64		127	340	41
	146	391	41		146	165	19
	176	78	8		176	39	7
^{92}Mo	52	9292	1595	^{110}Pd	52	4578	735
	58	7939	1214		58	3666	574
	63	7227	1151		63	2821	421
	68	5796	902		68	2271	301
	75	4813	846		75	1764	219
	83	3295	450		83	1289	150
	94	2334	290		94	912	109
	109	967	109		109	431	41
	127	405	39		127	246	21
	146	204	18		146	168	15
	176	88	7		176	45	3
^{108}Pd	52	4591	701	^{106}Pd	52	5801	791
	58	3601	541		58	4234	551
	63	2980	411		63	3896	512
	68	2180	309		68	3214	419
	75	1558	219		75	2310	314
	83	1188	140		83	1504	219
	94	680	81		94	860	110
	109	338	42		109	398	42
	127	240	24		127	190	18
	146	168	14		146	109	8
	176	43	4		176	32	2

Target	θ_L (mrad)	$\frac{d\sigma(\theta_L)}{d\Omega}$ (mb/sr)	total error (mb/sr)	Target	θ_L (mrad)	$\frac{d\sigma(\theta_L)}{d\Omega}$ (mb/sr)	total error (mb/sr)
^{105}Pd	52	3601	621	^{104}Pd	52	3100	594
	58	2821	405		58	2600	398
	63	2541	339		63	2291	321
	68	2249	290		68	1928	298
	75	1687	199		75	1587	212
	83	1194	160		83	1113	101
	94	780	92		94	720	65
	109	348	32		109	310	26
	127	149	11		127	160	12
	146	105	8		146	120	9
	176	38	3		176	29	2
^{103}Rh	52	4360	698				
	58	3690	614				
	63	2925	349				
	68	2295	261				
	75	1899	278				
	83	1260	165				
	94	646	71				
	109	263	24				
	127	111	9				
	146	62	4				
	176	16	2				

Summary of measured differential fusion cross sections with ^{32}S projectiles at $E_{\text{lab}} = 114$ MeV.

Target	θ_L (mrad)	$\frac{d\sigma(\theta_L)}{d\Omega}$ (mb/sr)	total error (mb/sr)	Target	θ_L (mrad)	$\frac{d\sigma(\theta_L)}{d\Omega}$ (mb/sr)	total error (mb/sr)
Mo	52	1410	215	Ru	52	3689	598
	58	1210	191		58	2601	394
	63	1109	160		63	2475	361
	68	981	149		68	1793	250
	75	825	132		75	1314	194
	83	599	81		83	870	91
	94	349	43		94	585	62
	109	146	12		109	412	38
	127	68	5		127	260	22
	146	38	3		146	186	14
	176	10	1		176	44	3
Ru	52	3432	511	Pd	52	1578	239
	58	2691	399		58	1256	182
	63	2281	298		63	1012	145
	68	2065	302		68	824	121
	75	1648	248		75	640	91
	83	1099	140		83	580	72
	94	742	70		94	398	43
	109	241	22		109	170	16
	127	76	6		127	80	7
	146	36	3		146	52	4
	176	18	2		176	17	2
Pd	52	1101	178	Mo	52	3132	429
	58	960	147		58	2429	365
	63	825	121		63	2097	301
	68	784	115		68	1904	290
	75	521	72		75	1120	172
	83	343	41		83	684	90
	94	201	19		94	426	45
	109	86	7		109	160	15
	127	42	3		127	74	6
	146	32	2		146	62	4
	176	11	1		176	18	2

Target	θ_L (mrad)	$\frac{d\sigma(\theta_L)}{d\Omega}$ (mb/sr)	total error (mb/sr)	Target	θ_L (mrad)	$\frac{d\sigma(\theta_L)}{d\Omega}$ (mb/sr)	total error (mb/sr)
^{103}Rh	52	1901	296				
	58	1250	184				
	63	1108	172				
	68	954	148				
	75	703	101				
	83	563	15				
	94	295	32				
	109	125	11				
	127	42	3				
	146	26	2				
	176	8	1				

Summary of measured differential fusion cross sections with ^{36}S projectiles at $E_{\text{lab}} = 120$ MeV.

Target	θ_L (mrad)	$\frac{d\sigma(\theta_L)}{d\Omega}$ (mb/sr)	total error (mb/sr)	Target	θ_L (mrad)	$\frac{d\sigma(\theta_L)}{d\Omega}$ (mb/sr)	total error (mb/sr)
^{104}Ru	52	8640	1351	^{102}Ru	52	7200	1195
	58	5731	891		58	4801	745
	63	4128	619		63	3450	476
	68	2637	390		68	2198	319
	75	1792	239		75	1465	208
	83	841	96		83	698	70
	94	543	49		94	453	43
	109	311	29		109	269	24
	127	230	21		127	209	18
	146	131	11		146	123	11
	176	41	3		176	36	3
^{101}Ru	52	7690	1257	^{100}Ru	52	5676	941
	58	5290	741		58	3990	693
	63	4260	619		63	3474	561
	68	3301	450		68	2195	329
	75	2078	308		75	1677	245
	83	1120	159		83	917	121
	94	791	15		94	579	56
	109	517	48		109	291	26
	127	340	30		127	196	17
	146	261	21		146	144	11
	176	78	6		176	41	4
^{100}Mo	52	9241	1534	^{98}Mo	52	11800	1743
	58	6258	991		58	7590	1250
	63	4901	761		63	6201	975
	68	3305	457		68	4670	709
	75	2387	349		75	2698	361
	83	1142	129		83	1498	150
	94	742	70		94	971	89
	109	259	23		109	578	50
	127	194	17		127	439	41
	146	156	12		146	391	35
	176	41	4		176	91	6

Target	θ_L (mrad)	$\frac{d\sigma(\theta_L)}{d\Omega}$ (mb/sr)	total error (mb/sr)	Target	θ_L (mrad)	$\frac{d\sigma(\theta_L)}{d\Omega}$ (mb/sr)	total error (mb/sr)
^{96}Mo	52	9989	1699	^{94}Mo	52	6954	1141
	58	6425	995		58	5294	749
	63	5261	734		63	4601	691
	68	3504	415		68	3297	457
	75	2263	325		75	2501	344
	83	1299	149		83	1803	195
	94	923	89		94	1125	109
	109	501	46		109	587	55
	127	360	32		127	401	36
	146	255	21		146	291	26
	176	76	5		176	71	5
^{92}Mo	52	5501	995	^{110}Pd	52	4891	701
	58	3578	491		58	3921	609
	63	2740	409		63	2910	423
	68	1840	259		68	2381	351
	75	1142	140		75	1832	288
	83	561	57		83	1318	150
	94	360	34		94	942	91
	109	192	17		109	420	40
	127	142	12		127	201	18
	146	109	9		146	120	11
	176	39	4		176	31	3
^{108}Pd	52	6094	937	^{106}Pd	52	5608	891
	58	3820	615		58	3423	499
	63	3240	465		63	2999	455
	68	2001	301		68	1690	245
	75	1257	154		75	1200	139
	83	631	61		83	601	61
	94	379	35		94	384	37
	109	258	22		109	219	19
	127	179	15		127	181	16
	146	135	12		146	122	11
	176	39	3		176	36	3

Target	θ_L (mrad)	$\frac{d\sigma(\theta_L)}{d\Omega}$ (mb/sr)	total error (mb/sr)	Target	θ_L (mrad)	$\frac{d\sigma(\theta_L)}{d\Omega}$ (mb/sr)	total error (mb/sr)
^{105}Pd	52	2670	456	^{104}Pd	52	2564	376
	58	1680	249		58	1998	314
	63	1441	218		63	1651	247
	68	891	135		68	1307	179
	75	599	90		75	911	95
	83	299	35		83	597	56
	94	269	25		94	380	36
	109	201	18		109	210	19
	127	141	12		127	188	16
	146	111	9		146	108	9
	176	35	3		176	40	3
^{103}Rh	52	4212	659				
	58	2759	415				
	63	2279	327				
	68	1961	305				
	75	1199	169				
	83	768	83				
	94	379	36				
	109	169	14				
	127	109	9				
	146	85	7				
	176	24	2				

Summary of measured differential fusion cross sections with ^{36}S projectiles at $E_{\text{lab}} = 114$ MeV.

Target	θ_L (mrad)	$\frac{d\sigma(\theta_L)}{d\Omega}$ (mb/sr)	total error (mb/sr)	Target	θ_L (mrad)	$\frac{d\sigma(\theta_L)}{d\Omega}$ (mb/sr)	total error (mb/sr)
^{104}Ru	52	4312	637	^{98}Mo	52	5132	753
	58	2951	450		58	3600	473
	63	2140	301		63	3102	469
	68	1297	180		68	2149	310
	75	871	95		75	1298	189
	83	419	40		83	747	85
	94	279	26		94	481	46
	109	153	14		109	290	25
	127	115	10		127	219	20
	146	67	6		146	189	17
	176	23	2		176	45	4
^{100}Mo	52	4513	659				
	58	3142	457				
	63	2409	369				
	68	1691	243				
	75	1240	180				
	83	593	80				
	94	383	41				
	109	139	12				
	127	101	9				
	146	81	7				
	176	19	2				

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